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PHYSICS OF THE MOON

SELECTED TOPICS CONCERNING LUNAR EXPLORATION

Edited by George C. Bucher and Henry E. Stern

George C. Marshall Space Flight Center
Huntsville, Ala.

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PHYSICS OF THE MOON

SUMMARY

This volume consists of thirteen papers dealing with lunar physics, and is based upon a series of symposia conducted at Marshall Space Flight Center in the fall of 1963. The writers are members of the Research Projects Laboratory of the Center. Topics include The Moon's History, Physical Characteristics of the Lunar Surface, The Lunar Atmosphere, Energetic Radiation Environment of the Moon, The Lunar Thermal Environment, A Lunar Scientific Mission, Some Suggested Landing Sites for Exploration of the Moon, Environmental Control for Early Lunar Missions, and Advanced Life Support Techniques.

INTRODUCTION

In the fall of 1963, the Research Projects Laboratory of the George C. Marshall Space Flight Center conducted a series of symposia in which members of the laboratory presented lectures on selected topics related to lunar physics. The symposia were held at MSFC, primarily for the purpose of better acquainting Center personnel with known information about the moon and the planned exploration of the moon.

This volume consists of a number of papers on most of the subjects covered in the symposia. The volume is divided into two sections: Section I describes some of the characteristics of the moon and its environment; Section II describes some aspects of a scientific lunar exploration program.

Man's knowledge of the moon is quite fragmentary, as the contents of this volume will readily show. Unmanned lunar payloads, such as the phenomenally successful Rangers VII, VIII, and IX, will provide much additional valuable knowledge. However, only when man finally sets foot on the moon and conducts a comprehensive scientific exploration program will his knowledge become fairly complete.

SECTION I
CHARACTERISTICS OF THE MOON

Chapter 1

THE MOON'S HISTORY

By

Ernst Stuhlinger *

The early history of the moon is as dark as the early history of the earth. Both came into existence about 4.5 billion years ago. Unlike the earth, the moon completed the decisive phases of its evolution during the first few hundred million years of its life. Since then, it must have remained almost unchanged. When the first living beings that were capable of seeing appeared on earth one or two billion years ago, they probably saw the moon much the same as we see it today.

A number of theories were offered on the origin of the moon. Sir George Darwin [1], in 1898, developed the idea that the moon was pulled out of the earth by solar gravitational forces at a time when the earth was still in a molten stage. However, even long before Darwin's theory, in 1850, Roche [2] had shown that the moon could never have been in the very close vicinity of the earth without breaking up. In fact, when a celestial body moves around another one, a differential force between the gravitational and the centrifugal forces develops within the body which tends to break it up. As long as this difference force is small, the breakup tendency is counteracted by internal gravity forces. Roche showed that for each two-body system, a critical distance exists below which breakup occurs. This critical distance, the Roche limit, is equal to 18,500 km in the earth-moon system (Fig. 1). In this derivation of the Roche limit, cohesive forces were neglected, and only internal gravitational forces were considered.

Another school of thought assumes that the moon, and also the planets, originated in clouds of hot gas. Condensation of the gas at discrete places led to the formation of planets and moons. It seems, though, that severe difficulties arise when condensation of a tenuous gas is considered as the initial step in the formation of a planet or a moon. A very interesting modification of the gas cloud theory was developed by Alfvén in 1954 [3,4]. It starts with a central body, such as a newly formed star or planet, possessing a magnetic field and surrounded by a plasma. Neutral gas atoms fall from great distances towards this central body under the action of gravity forces. Alfvén assumed that the atoms become ionized by interaction with the plasma in the vicinity of the central body as soon as their kinetic energy has become equal to their ionization energy, as expressed by equation 1:

* Director, Research Projects Laboratory

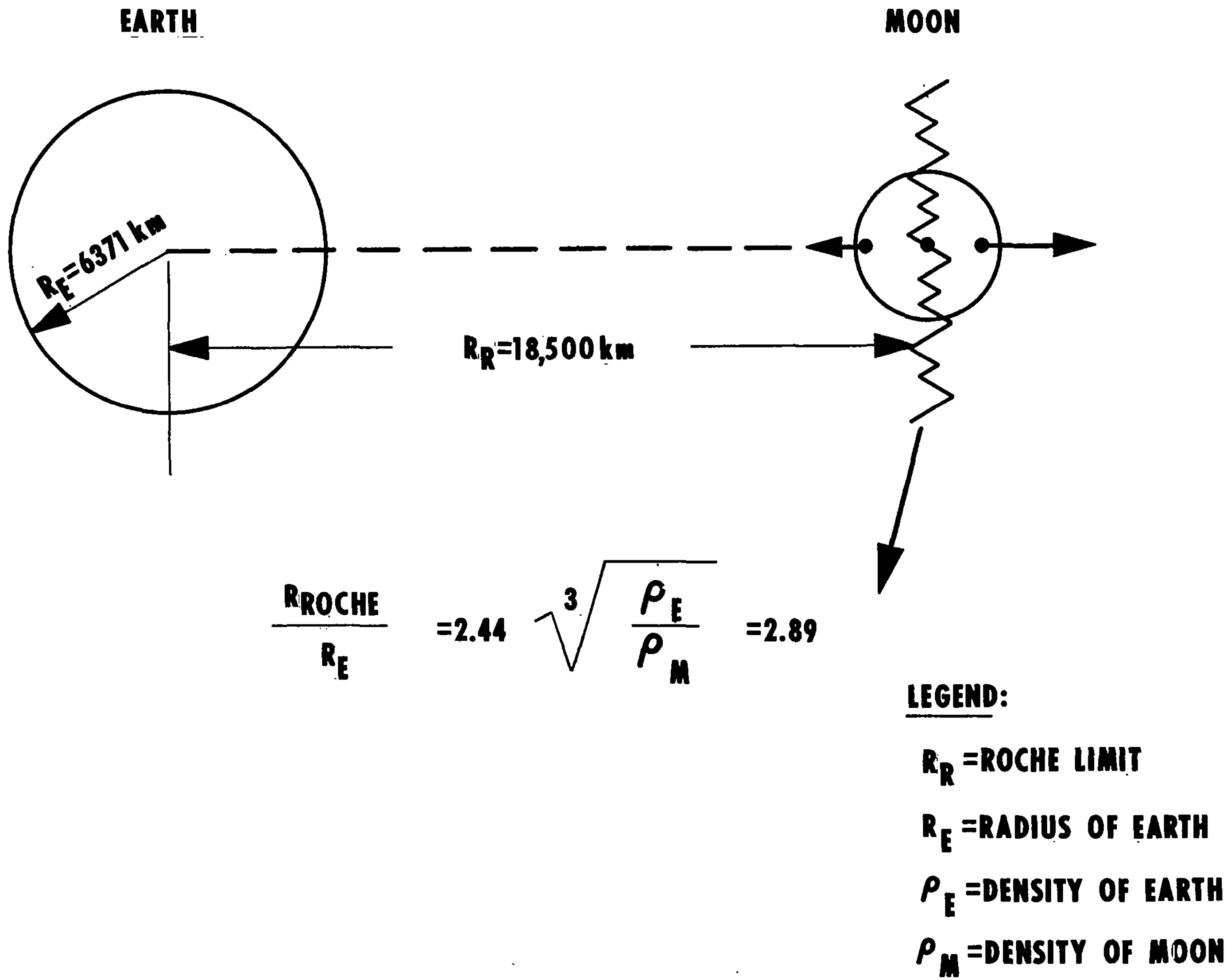

FIGURE 1. DIAGRAM OF THE EARTH-MOON SYSTEM, ILLUSTRATING THE ROCHE LIMIT

$$\frac{1}{2} m v_c^2 = e V, \qquad (1)$$

where v_c = critical velocity; V = ionization potential; m = atomic mass; and e = ion charge. As soon as the atom is ionized, it is forced by the magnetic field into a trajectory which, in essence, follows a helical path around the field lines. At the same time, centrifugal forces become noticeable and keep the ions from falling into the central body, provided that they were not formed too close to one of the poles. This magnetic stopping of the falling particles occurs at a critical distance R_c where the potential energy equals the critical kinetic energy:

$$\gamma \frac{mM}{R_c} = \frac{1}{2} m v_c^2; \qquad (2)$$

or, with equation 1,

$$R_c = \frac{\gamma M}{V} \frac{m}{e} \qquad (3)$$

where γ = gravitational constant, and M = mass of central body. Hence, we should expect that matter will be accumulated as a plasma around a central body at about the distance R_c. Electromagnetic forces will transfer angular momentum from the central body into the plasma. Planets or moons will later develop out of the plasma at about the distance R_c. Figure 2 shows that the critical velocities of a number of elements are indeed of the correct order to account for planets and moons of our solar system. It need not be expected that each of the newly formed planets and moons consists only of that element whose ionization energy corresponds to its distance from the central body; actually, a mixing of different elements will occur over wide regions around the central body because of differences in condensation temperature, gas density, ionization cross section, and other parameters influencing the ionization and capture of falling atoms. A more serious criticism of Alfvén's theory arises from the fact that the ionization cross sections of atoms, if they are to be ionized by collisions with ions, are almost vanishingly small at the velocities in question. Transfer of the kinetic energy of the falling atoms to electrons, which are more efficient ionizing particles, would be required.

It appears that the most widely accepted theory for the formation of planets and moons is the accretion theory. Fragments of matter, orbiting in loose clouds or rings around a central body, accumulated slowly under the action of gravitational forces. Scooping up more and more solid particles, the newly formed

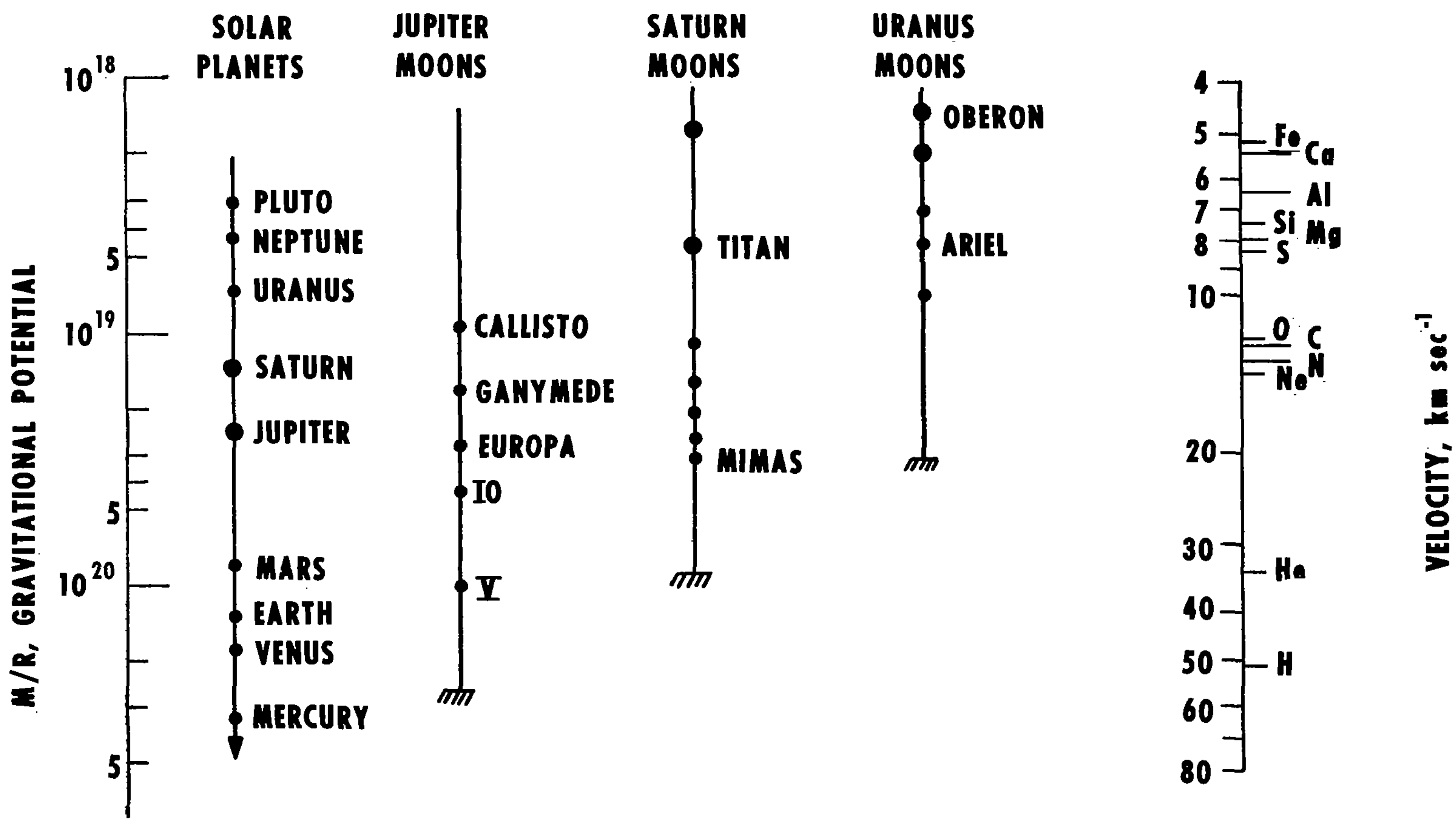

FIGURE 2. DIAGRAM OF SOLAR PLANETS, AND OF SOME PLANETARY MOONS
Left ordinate: potential of central force fields; right ordinate: free fall velocity in central force fields. Elements are shown at places where free fall kinetic energies of atoms are equal to their ionization energies (Alfvèn, 3).

bodies gradually swept all orbiting fragments from the regions around the central body. This theory, which is supported by Kuiper, [5], Urey [6, 7], and others, seems to present fewer difficulties than the gas cloud theory. A body formed by accretion would not be hot during its formation. It has been speculated that it may heat up, and even melt, at later times under the action of radioactive heating; however, Urey [8], and later MacDonald [9], have shown that our moon could not reach melting temperatures from radioactive heating alone. There is even a strong belief today that the moon never was in a molten, or at least plastic, state during the last four billion years. This belief is derived from the shape of the moon. If the moon had been capable of interior flow during that period of time, it would have acquired an equatorial bulge of about 50 m altitude under the centrifugal forces of its axial rotation. Actually, its equatorial bulge is about 1 km high. Furthermore, the moon has an oblong shape with its long axis directed toward the earth. This oblong shape must have been caused by gravitational forces from the earth. Under conditions as they prevailed during the past four billion years, and assuming a plastic interior, this elongation should be about 40 m; actually, it is about 1000 m.

Jastrow [10] pointed out that the large equatorial bulge and the moon's oversized oblong shape must have been formed at a time when the moon was much closer to the earth. At that time, it rotated faster around its axis and was subject to larger gravitational forces. When it moved out to greater and greater distances from the earth, it did not flow back to a more spherical shape, but instead retained its original form. This indicates that during the past four billion years, the interior of the moon was too rigid to allow a change in shape.

The question of whether the moon was in a molten, or at least a plastic, state at any time during its history can probably be answered as soon as a lunar satellite has been established and its orbit accurately surveyed. While the shape, the mass, and the mean density of the moon are known with good precision, the mass distribution in its interior is unknown. Certain irregularities in a lunar satellite orbit will permit determination of the density as a function of the radius. If it should turn out that the moon has a heavy core of iron, for example, one may conclude that the moon was indeed molten at an earlier time, allowing the heavy elements to accumulate at its center.

It appears likely that the moon came into being as a planet around the sun, rather than as a satellite around the earth. In this case, it must have been captured by the earth soon after its formation. The mechanism of this process was difficult to understand for a long time. In 1955, a paper was published by Gerstenkorn [11] in which a very plausible explanation was given. First, Gerstenkorn argues that the moon must have been captured in a very eccentric, almost parabolic orbit; capturing was accomplished by very severe tidal action during perigee. This process is dynamically possible, even when earth and moon turn in the same direction. However, in that case the eccentric orbit would transform very slowly into a more circular orbit. The situation is different when capturing in a retrograde orbit is assumed. In that case, transition into a circular, forward orbit in a relatively short time is possible.

At the present time, the moon moves in an almost circular, forward orbit. Its orbital plane is not far from the equatorial plane of the earth. Tidal action on the earth continuously decreases the energy of the earth-moon system. Since the total angular momentum of the system must remain constant, the moon spirals outward as illustrated in Figure 3. In doing so, its energy increases, but that of the rotating earth decreases. Starting out with these facts, and making reasonable assumptions regarding frictional forces of the tides, Gerstenkorn calculated backward from the present conditions and arrived at the following picture which describes the past history of the moon in a remarkably plausible fashion [12].

During the early history of the solar system, the moon was a planet; it was captured by the earth during a close encounter in a highly elliptic, retrograde orbit whose plane was inclined 149 degrees toward the earth's equatorial plane. The earth rotated around its axis about ten times faster at that time than it does today. The vector diagram of the moon's orbital motion and the earth's axial motion is depicted in Figure 4a. Tidal forces on the earth slowed down the earth's rotation, and the moon's orbital motion. Besides, they changed the orbiting plane of the moon in such a way that the resulting angular momentum of the system remained constant. The eccentricity of the lunar orbit decreased. At one time, the orbit inclination of the moon with respect to the equatorial plane of the earth reached 90 degrees; the moon moved over the earth's poles (Fig. 4b). The orbital inclination continued to change, making a forward orbit out of the original retrograde orbit. Somewhat later, the moon reached its closest distance from earth; Gerstenkorn's theory shows that the minimum distance is reached when

$$\omega_{moon} = \omega_{earth} \cos \epsilon \qquad (4)$$

where ϵ is the angle between the two momentum vectors and ω is the angular velocity (Fig. 4c). From this time on, the moon received energy as well as angular momentum from the earth. It gained distance, but it continued to move its orbiting plane closer to the equatorial plane of the earth. At the present time, earth and moon move as shown in Figure 4d. Figure 5 illustrates this process from capture to the present state (Öpik, [13]).

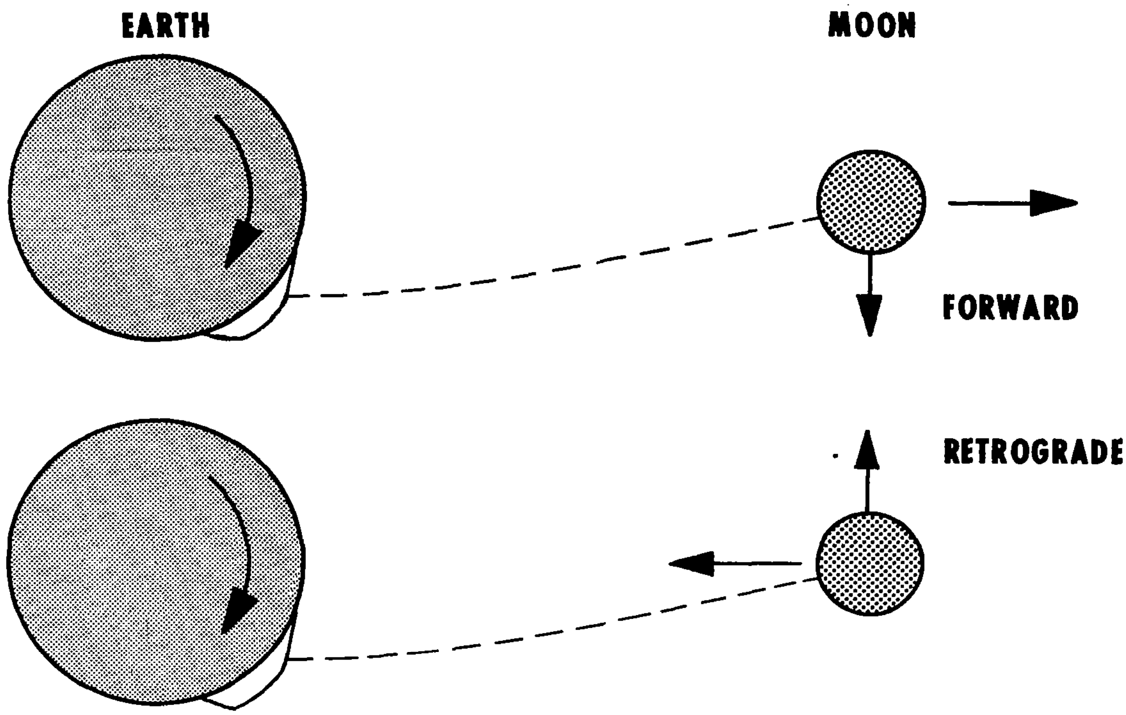

FIGURE 3. EFFECT OF TERRESTRIAL TIDAL WAVE ON LUNAR TRAJECTORY

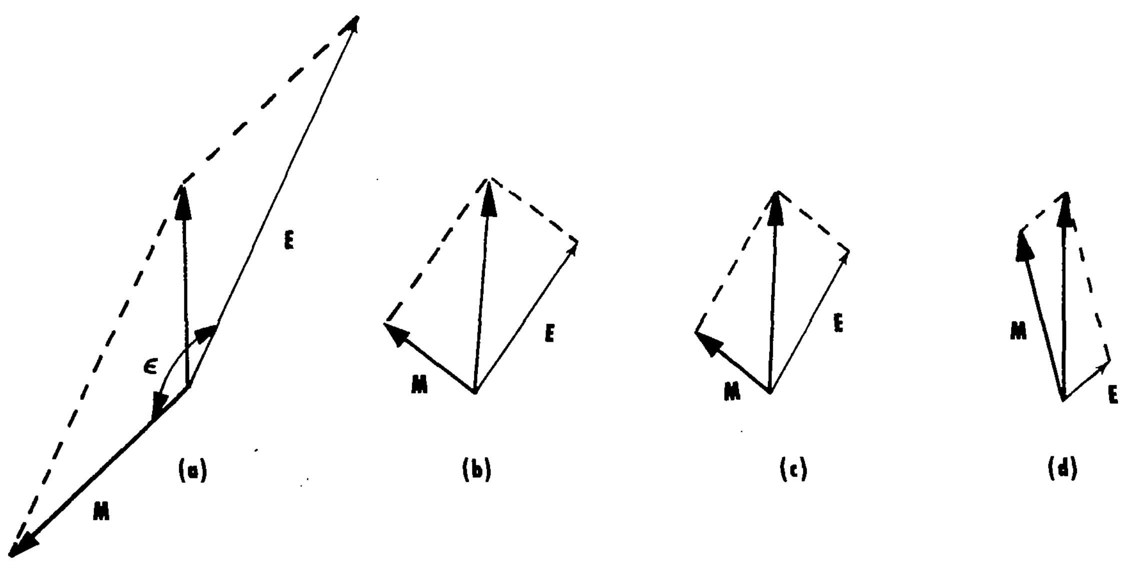

FIGURE 4. VECTOR DIAGRAMS OF EARTH-MOON SYSTEM DURING EVOLUTION

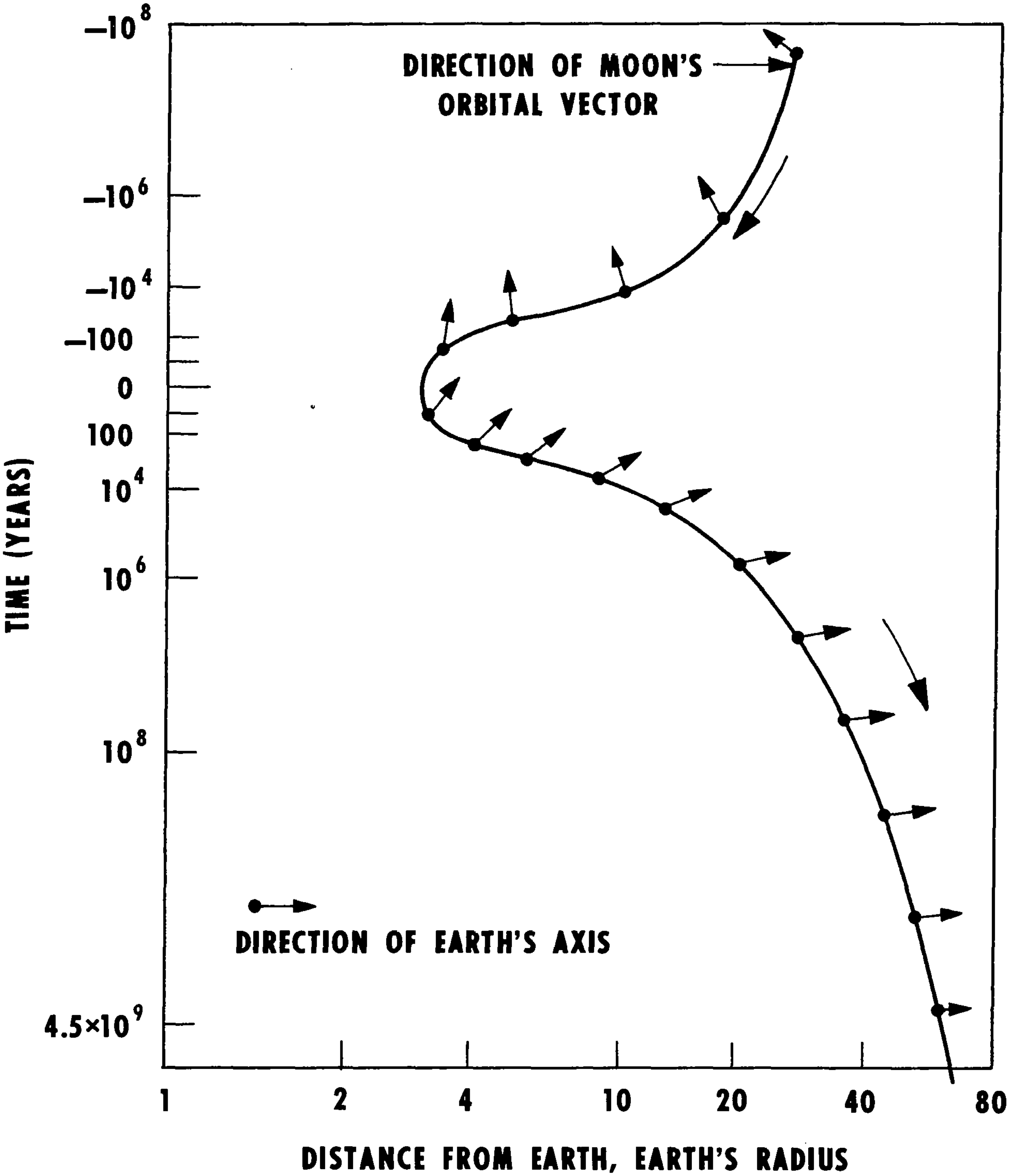

FIGURE 5. RADIUS AND MOMENTUM DIRECTION OF LUNAR ORBIT DURING EVOLUTION

The author of this theory pointed out one potential difficulty. Depending on the angle ϵ, equation 4 may lead to a minimum distance which is smaller than the Roche limit where the moon is expected to break up. In Gerstenkorn's calculations, the minimum distance was found equal to the Roche limit. The moon reached that point 2.5 billion years ago. Whether the moon really did approach the earth to this distance (18,500 km), and whether it lost mass at that point, resulting from a breakup, is not known. If the moon really underwent some breakup, there is a possibility that part of its mass, after moving for some time through complicated orbits, fell to earth and helped to build the continents: another part, in the form of fragments, may have fallen to the moon where the moon craters formed under their impacts. The tidal waves on earth would have been gigantic at the time when the moon was close to the earth. Their height, being inversely proportional to the third power of the lunar distance, may have amounted to 10 km, and even more. High tide occurred every two and one-half hours.

At present, the slow increase of the moon's distance from the earth, and the concomitant reduction of the earth's rotational speed, lengthen the earth day by one millisecond per century. During the Cretaceous period, the day was 17 minutes shorter; a Paleozoic day was one and one-half hours shorter. When the moon was at its closest distance from the earth, the day had a length of only five hours.

Aristotle, more than 2000 years ago, noted that the moon looks toward earth always with the same face, and he concluded that its rotational speed around its axis is equal to its orbital angular velocity. Actually, the lunar orbit is elliptic, with a mean eccentricity of 0.055. Its orbital velocity varies between perigee and apogee, while its axial rotation is constant. This situation leads to a longitudinal libration of ± 7° 9'. At the same time, the moon is subject to a libration of 6° 44' in latitude because of an inclination of the lunar orbit toward the ecliptic of 5° 9', and of an inclination of the lunar axis toward the ecliptic of 1° 35' (Fig. 6). Both these librations have a period of 27.32 days which is equal to the period of the axial rotation of the moon, and to the length of the sidereal month. The orbital period of the moon with respect to the earth is 29.53 days. Besides the longitudinal and the latitudinal librations, there is also a diurnal libration, caused by the varying distance of the observer on the earth from the plane of the ecliptic. This libration, with a period of 24 hours, has an angle of ±57' of arc. All these librations together result in about 59 per cent of the moon's surface becoming visible to the earthbound observer during a 30-year interval.

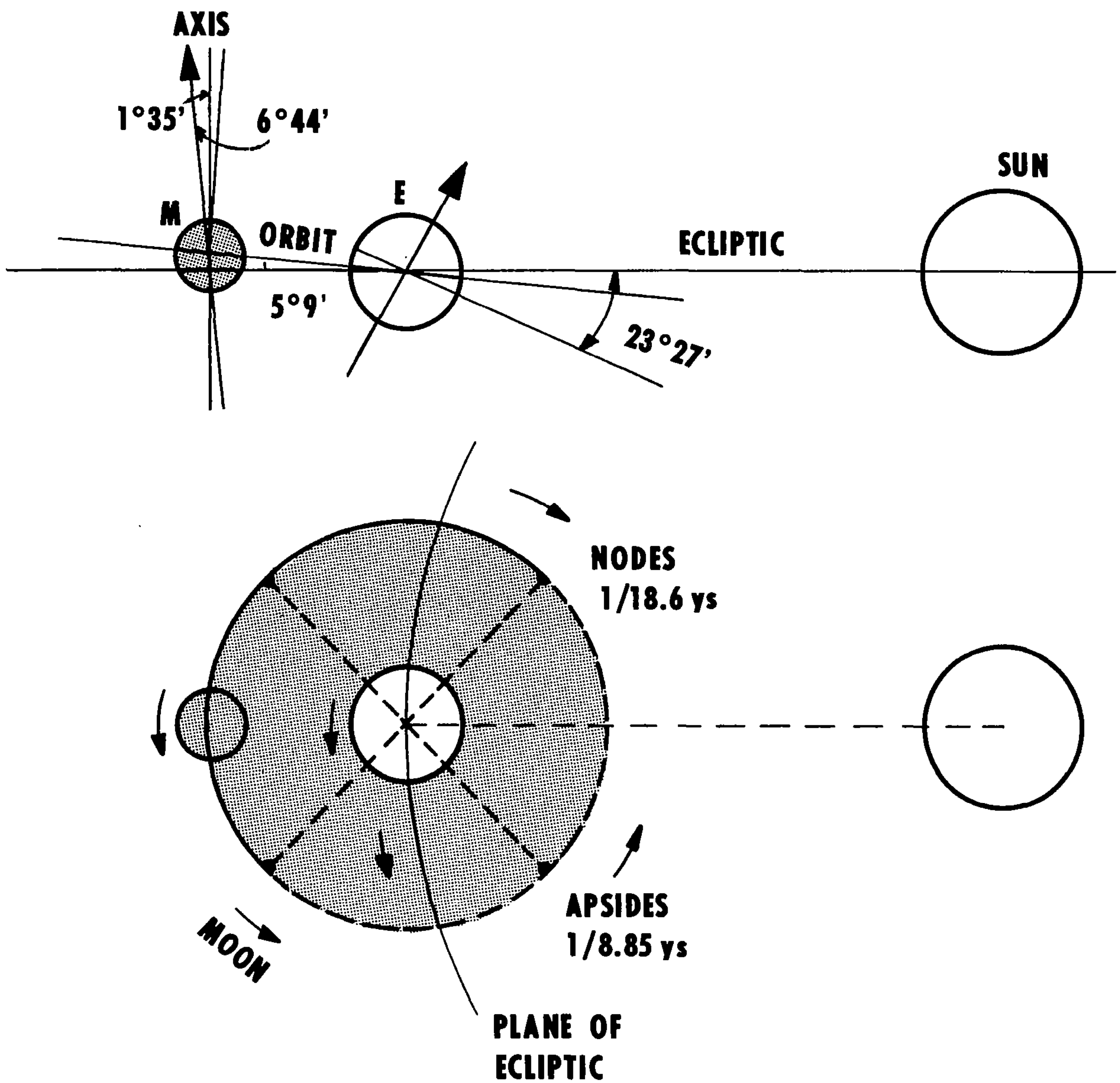

FIGURE 6. ANGULAR RELATIONS BETWEEN THE EARTH'S AND THE MOON'S AXIAL AND ORBITAL MOMENTS

Important data of the moon and of its orbit around the earth are listed in Tables I and II. Very roughly, its diameter is 1/4, its volume 1/50, its mass 1/81, its density 2/3, and its surface gravity 1/6 those of the earth. As seen from space, the superposition of the moon's motion around the earth and the earth's motion around the sun result in a slightly undulating path of the moon around the sun. The amplitude of the undulation is only 1/5 of 1 per cent of the sun-moon distance (Fig. 7). In fact, the lunar path around the sun is always concave. The force with which the sun attracts the moon is about twice as great as the force with which the moon is attracted by the earth. The lunar trajectory in space may be considered as an orbit around the sun, slightly modified by the presence of the earth. The barycenter of the earth-moon system, around which both bodies rotate, lies about 1640 km underneath the earth's surface (Fig. 8). The neutral point between earth and moon, at which the gravitational forces of the two bodies cancel each other, has a distance of 38,400 km, or 10 per cent of the earth-moon distance, from the moon's center. It has been suggested that this point might be an ideal staging and rendezvous place for lunar expeditions. Besides this possible but somewhat questionable usefulness, the neutral point has no particular significance. The activity sphere of the moon is the region within which a spacecraft is considered to move in the central force field of the moon, while the earth acts as a perturbing body.

Distance and diameter of the moon can be determined by direct optical observations; its mass must be derived from perturbations which the sun, the earth, and other planets exercise upon the lunar orbit. One of the more conspicuous perturbations, the regression of nodes of the lunar orbit (Fig. 6), is caused by the equatorial bulge of the earth. The nodal points, or the two points where the lunar orbit intersects the plane of the ecliptic, precess in retrograde motion through a full cycle every 18.6 years. The line of apsides, connecting perigee and apogee, precesses in forward motion; its period is 8.85 years.

The orbiting velocity of a low lunar satellite is on the order of 1.6 km sec^{-1}. Besides giving valuable clues as to the internal mass distribution of the moon, lunar satellites will permit observation of many surface details. Telescopic observation from the earth's surface is limited by atmospheric disturbances. Photographs from the earth resolve lunar surface details down to a magnitude of about 200 m; in visual observation, a trained astronomer can distinguish objects down to about 50 m. A much better resolution in the vertical direction is possible when the shadow of a crater rim, a peak, or a mountain range is analyzed. Shortly before sunset, shadows can be observed until they are about 100 times as long as the shadow-producing objects. In this way, lunar altitudes can be determined down to a few meters (Fielder, [14]).

TABLE I

PHYSICAL DATA OF MOON AND EARTH

	MOON	EARTH	MOON / EARTH
RADIUS (km)	1738	6371	1/3.6
VOLUME (km^3)	2.2×10^{10}	1.8×10^{12}	1/50
MASS (metric tons)	7.35×10^{19}	5.97×10^{21}	1/81
DENSITY ($g\ cm^{-3}$)	3.34	5.52	2/3
DISTANCE FROM EARTH (km) (mean)	384 400		60 EARTH RADII
(max)	406 700		
(min)	356 400		
SURFACE GRAVITY ($cm\ sec^{-2}$)	162.0	980.67	1/6
ESCAPE VELOCITY ($km\ sec^{-1}$)	2.38	11.2	1/4.7
ORBITAL VELOCITY ($km\ sec^{-1}$)	1.02	29.77	1/29
ALBEDO, AVERAGE	0.07	0.29	1/4

TABLE II

~~PHYSICAL~~ orbital DATA OF THE MOON

SOLID ANGLE FROM EARTH	31'7"
MEAN ECCENTRICITY	0.055
INCLINATION OF LUNAR ORBIT TO ECLIPTIC	5°9'
INCLINATION OF LUNAR EQUATOR TO ECLIPTIC	1°32'
AXIAL ROTATION	27.32 days
SYNODIC ROTATION	29.53 days
SIDEREAL ROTATION	27.32 days
PERIOD OF NODES (RETROGRADE)	18.6 years
PERIOD OF LINE OF APSIDES (FORWARD)	8.85 years
SURFACE TEMPERATURE, day	134°C
night	−150°C
VISIBLE SURFACE AREA	59%

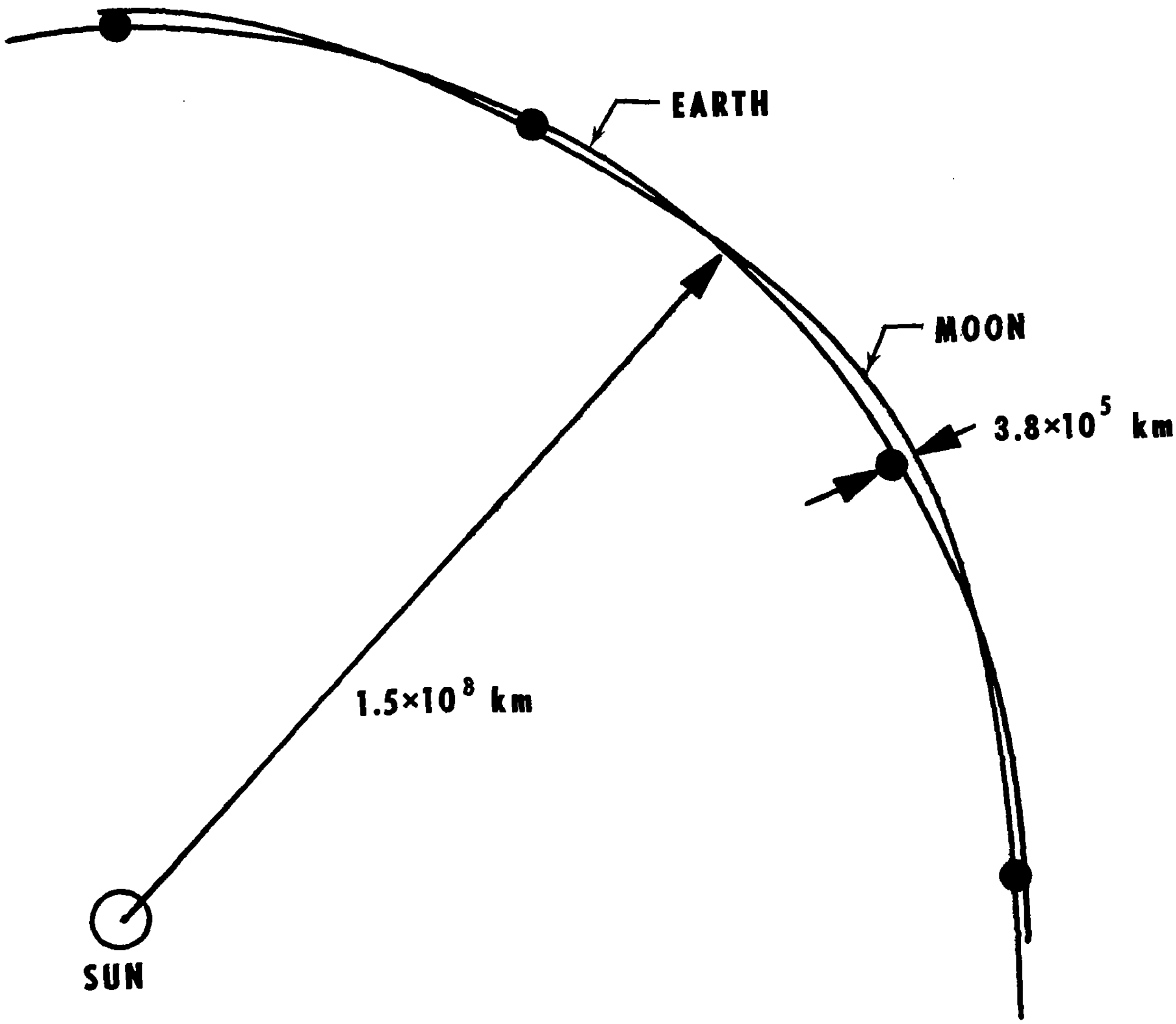

FIGURE 7. EARTH AND MOON ORBITS AROUND THE SUN

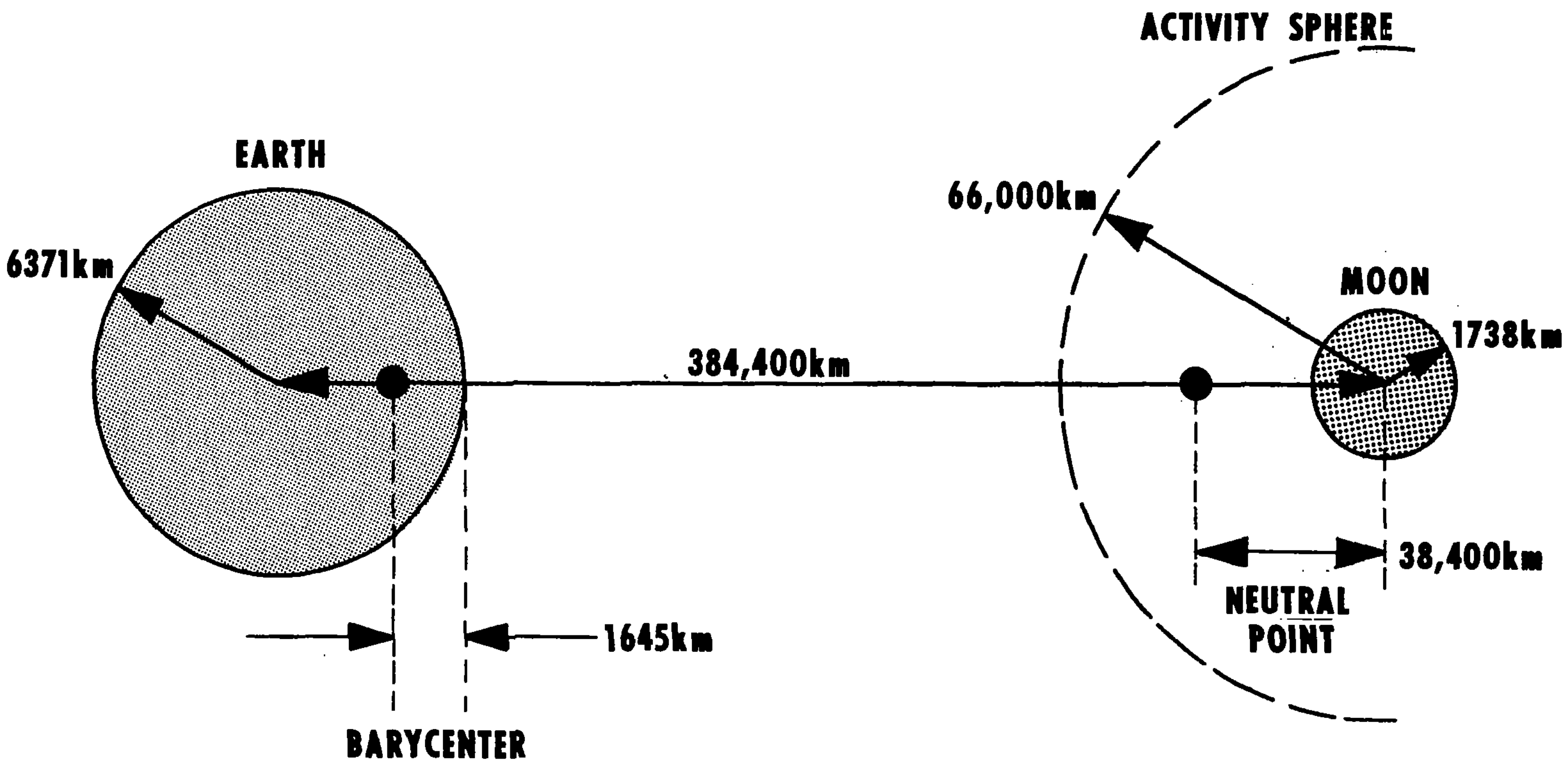

FIGURE 8. BARYCENTER, NEUTRAL POINT, AND SPHERE OF ACTIVITY OF EARTH-MOON SYSTEM

The best lunar photographs were probably made by G. P. Kuiper at the University of Arizona [15]. His department published a "Photographic Lunar Atlas" in 1960 with 280 reproductions of photographs of the lunar surface, an "Orthographic Atlas of the Moon" with selected photographs containing a precision coordinate grid and a longitude-latitude net with 2-degree intervals, and a "Rectified Lunar Atlas" which shows 30 by 30 degree fields of the lunar surface. Each field was photographed three times in the morning, at noon, and in the late afternoon. All these photographs were rectified by first projecting the original photograph on a three-foot white precision sphere, and then photographing each field from a direction normal to the surface of the globe at the centerpoint of the field.

To earthbound observers, the moon gives the image of an unchangeable, obviously dead body (Fig. 9). The most conspicuous features of its surface are the innumerable craters of various sizes, and the few large dark areas which have been called "maria" because they give the impression of seas. There are lowlands and uplands, mountain ranges with altitudes of more than 10 km, craters of 8 km depth, rills and walls, folds and ridges, and very strange ray systems which can be seen under certain light conditions. Figure 10 is a picture of the moon which was composed of two half-moon photographs. Crater Tycho, which displays a very conspicuous and brilliant ray system at full moon (Fig. 9), shows no rays when the angle between incident and reflected light is on the order of 90 degrees.

On the average, the lowlands are 2.5 km below the highlands. A photograph of the backside of the moon (Fig. 11), which was taken by a Russian moon probe in 1959, indicates that the front side contains more dark-colored lowlands than the backside. Besides optical observations, a variety of measurements on surface temperature, reflectivity of radio waves, and polarization of reflected radiation are possible from the earth [16, 17]. The amount of data from such measurements is very impressive; however, many of the conclusions implied by observations are still highly controversial. To date, we have no clear concept of the history of the moon, of its internal structure, of its surface features, of its heat balance, of its composition, of its mechanical properties, of its magnetic field, and of many other details. On the other hand, some facts seem to be established with a high degree of certainty. One of the best studies of the moon was published in 1893 by G. K. Gilbert [18]. Many of his explanations and conclusions were verified by later observations. In particular, his belief that the moon craters are the results of meteorite impacts, rather than of volcanic origin, is commonly accepted today. A meteorite crater should have a crater rim of a volume approximately equal to the volume of the crater itself; this seems to be true for most of the craters (Schröter's rule). Also, the material of the rims

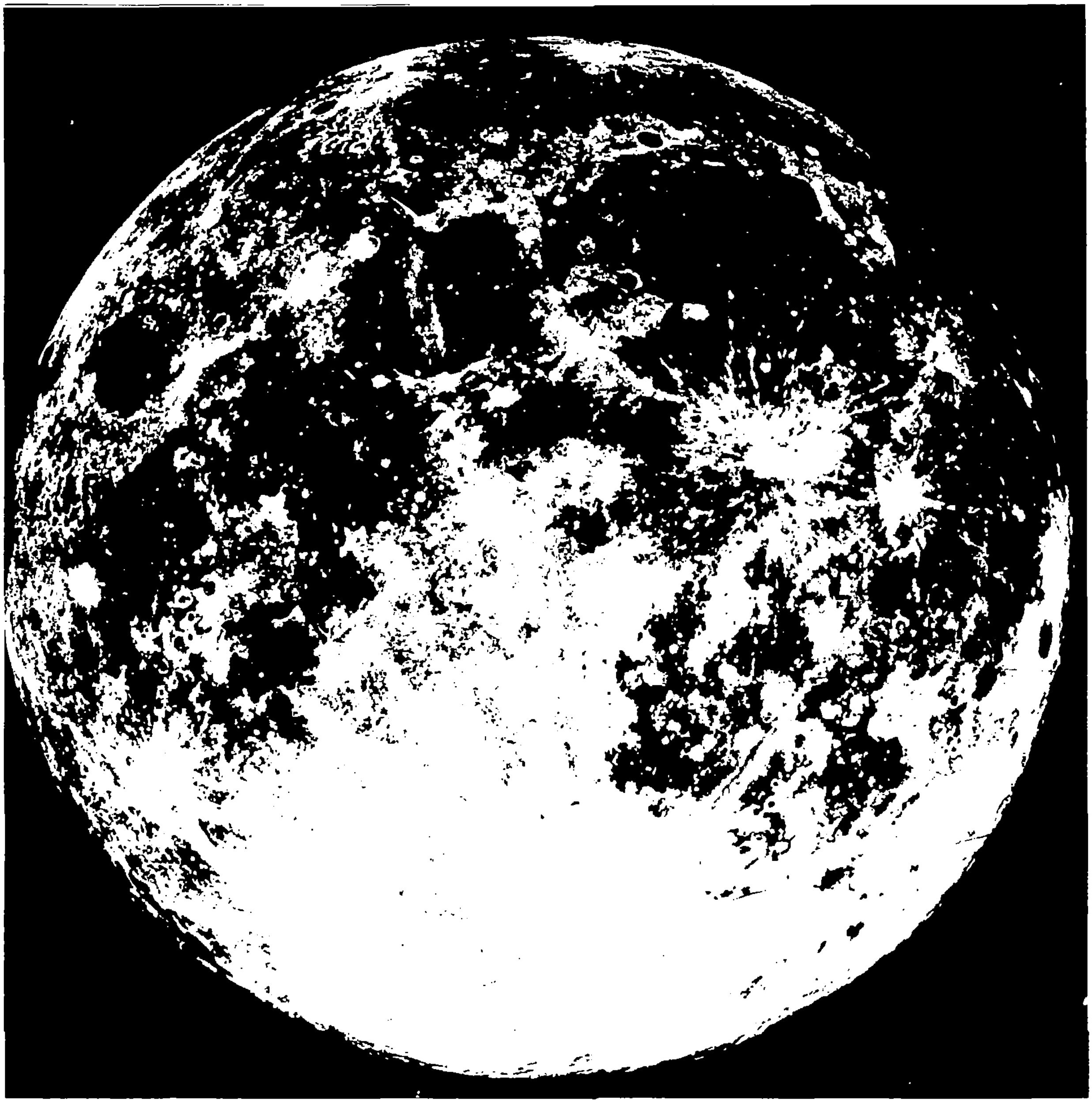

FIGURE 9. PHOTOGRAPH OF THE FULL MOON

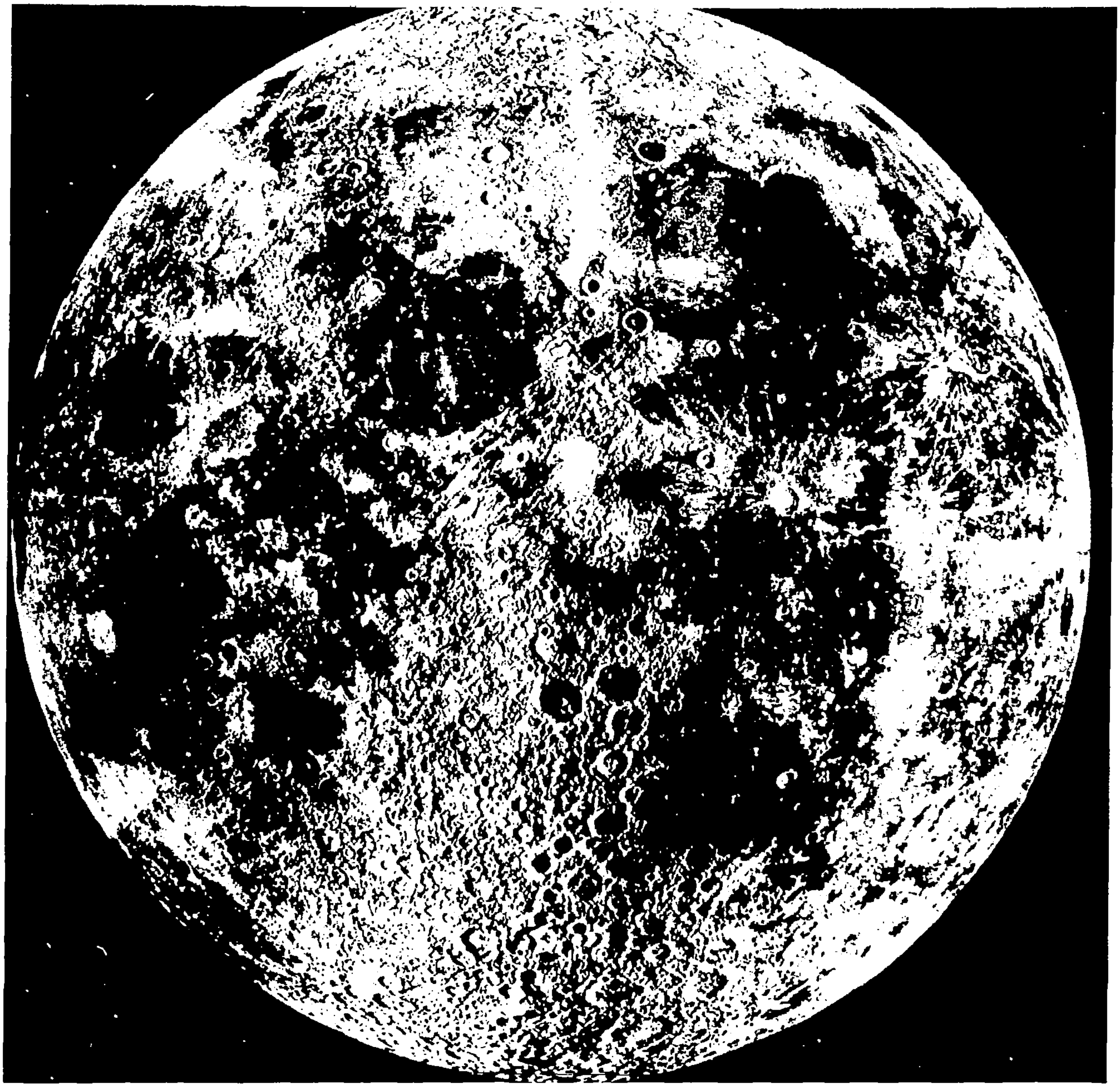

FIGURE 10. PICTURE COMPOSED OF TWO HALF-MOON PHOTOGRAPHS

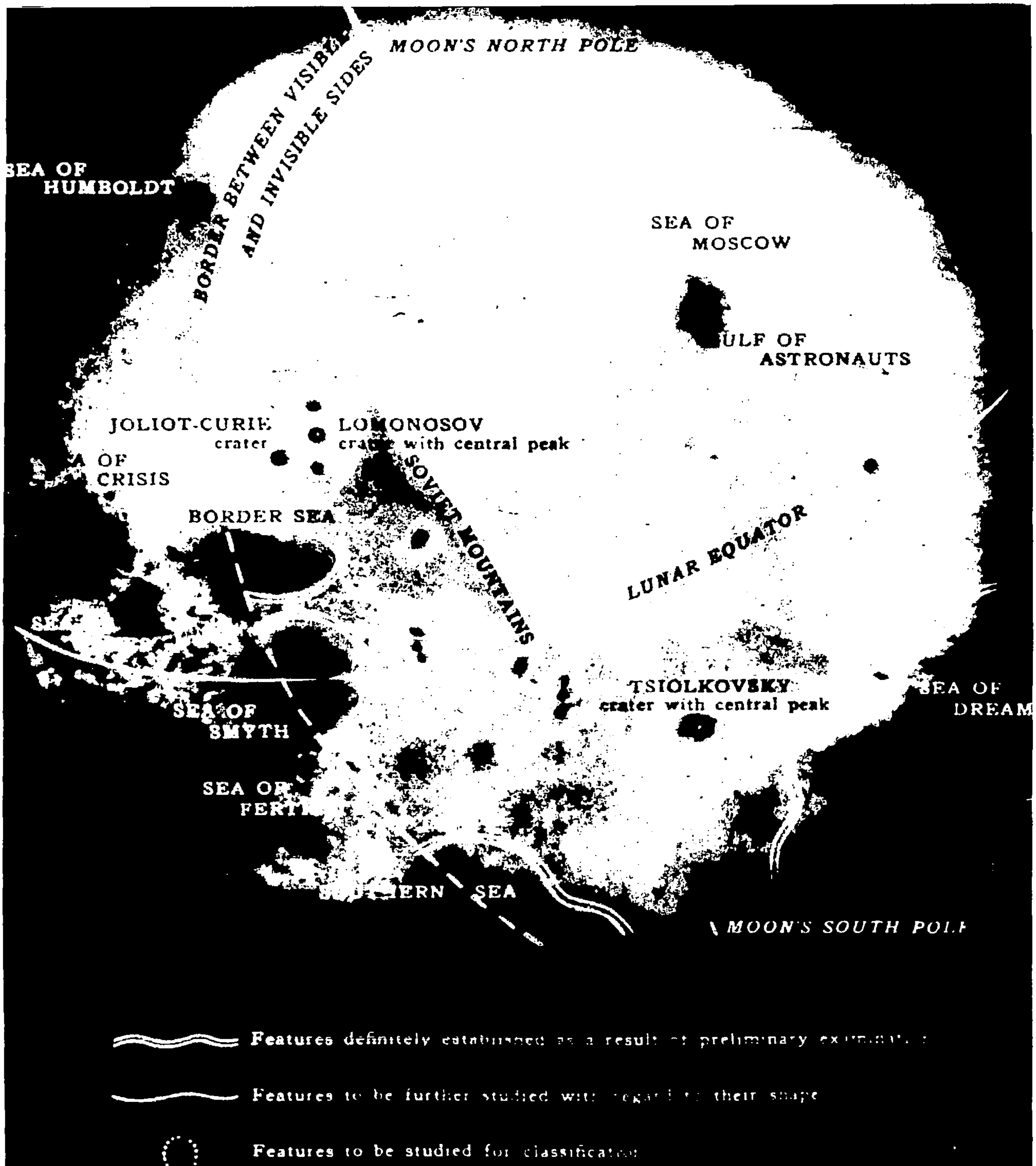

FIGURE 11. REAR SIDE OF THE MOON, PHOTOGRAPHED FROM LUNIK III (1959)

appear to be the same as the material between craters; in case of volcanic origin, the rim material should be different in appearance. There is a very small percentage of craters which do not show any rim structure although they must be of relatively young age; they are assumed to be of volcanic origin. Also, there are examples of rows of closely spaced craters which may have originated simultaneously as volcanic outbreaks from large subsurface faults. With the exception of these rare occurrences, however, it is assumed today that the moon craters were produced by impacting fragments from space. Urey [6] pointed out that the kinetic energy of a fragment falling to the moon with only lunar escape velocity is approximately equal to the chemical energy of the same mass of TNT; if the impact velocity is on the order of that of terrestrial meteoroids, the impact energy is about 100 times larger. This impressively large amount of energy per unit mass of impacting fragment implies the conclusion that most of the meteorites that produced the lunar craters were relatively small in size. One of the largest impact craters, the Mare Imbrium, about 800 km in diameter (Fig. 12), was probably generated by a fragment 200 km in diameter (Urey). Its kinetic energy at impact was equivalent to about ten billion H-bombs, each of one-hundred megaton size.

It is obvious that the craters differ in age. The younger ones show sharper rim lines and higher rims than the older ones. Although there was certainly no atmospheric erosion on the moon as we know it from earth, there must have been several eroding agents at work for geologically long times: meteorite impacts which tend to pulverize the surface material and to make it move downhill under the force of gravity; ultraviolet and particle radiation which leads to disintegration of surface material; the change between hot and cold which may cause some temperature cracking in the uppermost layer; and, finally, the seismic vibrations and shocks which occur during meteorite impacts and possibly during tectonic activities inside the moon.

It is very likely that even the young craters were generated three or four billion years ago, and that the long period since that time has been rather quiet and eventless. One reason for this belief is the fact that the surface of our earth, which presents a record of surface events of the last one or two billion years in the form of sedimentary rocks, shows almost no impact craters at all. Places such as the Grand Canyon of the Colorado, which afford a beautiful view of a cross section through vast regions of young and old sediments, do not reveal any impact craters. The few impact craters on the earth's surface, among them the Arizona Crater, the Henbury Crater in Australia, the Deep Bay Crater in Saskatchewan, Canada, the Noerdlinger Ries in Germany, the Chubb Crater near Hudson Bay, the Siberian meteor crater, and a few others, are far less in number than a corresponding selection of lunar impact craters. At the same time, we must assume that the earth is hit by meteoroids more frequently than the moon because of its

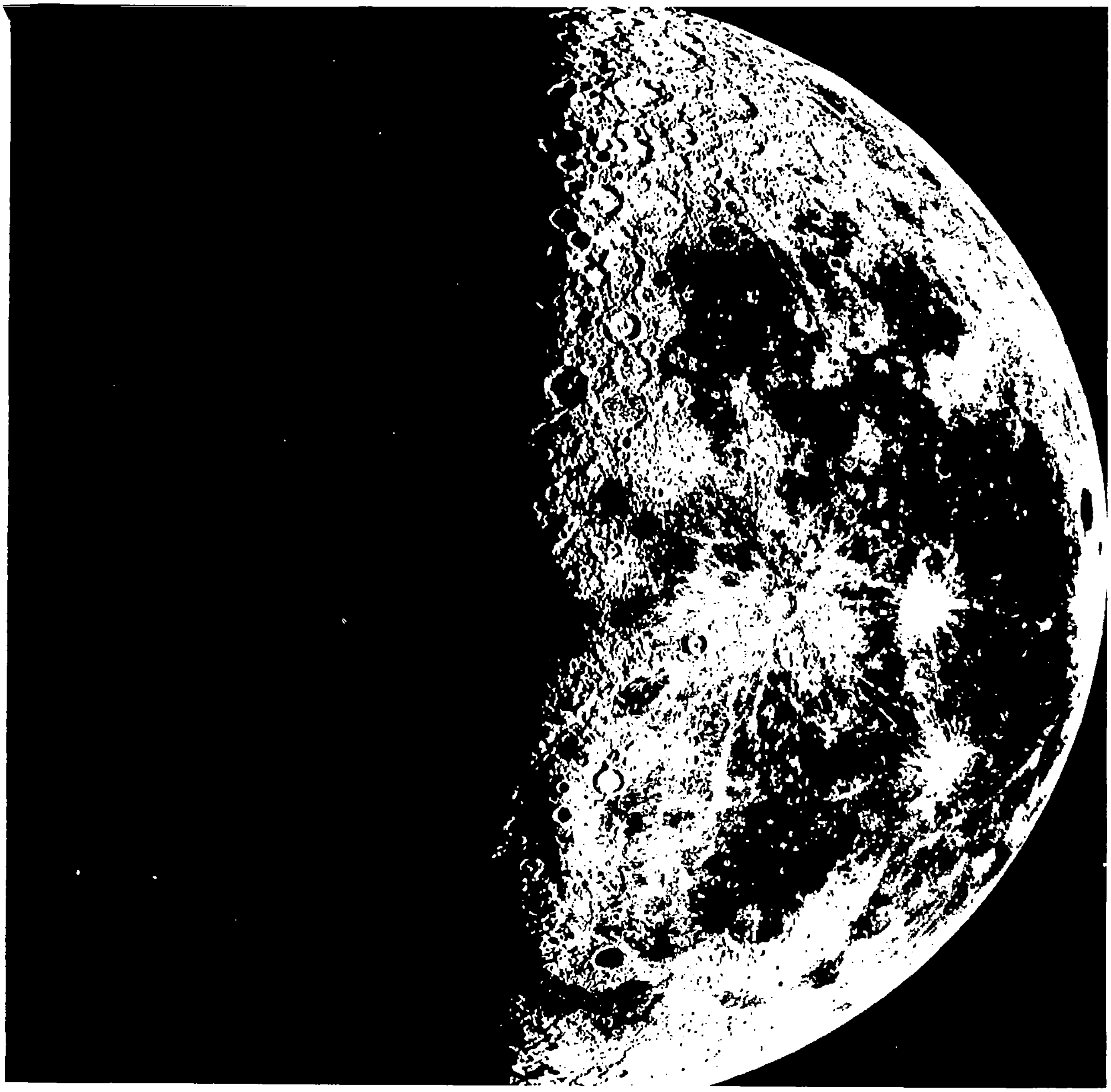

FIGURE 12. WEST* HALF OF MOON WITH MARE IMBRIUM

* The western half of the moon is to the right of an observer viewing from the northern hemisphere. For an observer at the center of the visible lunar circle, this (western) half is to his east.

greater attracting force. The obvious explanation is that meteorite impacts were frequent during the first billion years of the earth's and moon's histories, and that both together cleaned the region of their common solar orbit by sweeping up nearly all the fragments in that area. The moon kept an impressive record of that early phase of its history. On the earth, this early record was destroyed by the later geological events which occurred on the earth only.

Many of the craters and some of the lowlands on the moon are filled with dark material. Its very smooth, unbroken surface implies that this material consists of a lava-like substance which filled the craters and the lowlands by flowing into these regions, and by solidifying after an isostatic surface had been established locally. Urey assumes that a number of maria, among them Imbrium, Serenitatis, Crisium, Foecunditatis, Nectaris, and Humorum, were formed by collision, and that a subsequent lava flow filled them to a depth of 10 to 20 km. A look at Mare Humorum (Fig. 13) indeed conveys the impression that a liquid must have filled up a low region, including some smaller craters at its rim. Heavy material, such as iron, nickel, and olivine, should be found on their bottom; silicates and granite-like substances would have accumulated in the top layers. Other dark areas, such as Oceanus Procellarum, Mare Tranquilitatis, and Mare Nubium, may have been formed by the flow of lava into lowlands from adjacent impact craters.

The question of where the lava came from is still unanswered. Urey pointed out that the energy of an impacting fragment is sufficient to melt the material within a wide region around the point of impact, and that the lava may have been produced by the impact itself. However, it is not certain whether the better part of the impact energy would be available for the melting of large volumes of material. It seems more likely, as Kuiper and others have suggested, that the impact energy is absorbed in the shattering, pulverization, and ejection of material, in seismic action, and perhaps in some limited local melting. On the other hand, it is not likely that large amounts of molten lava existed in the interior of the moon at the time when the maria were formed. In fact, there is a strong probability that the moon was never hot enough to be near-fluid in its interior. Radioactive heating would not be sufficient to melt even the inner part of the moon, unless the moon formed at its beginning with an initial temperature of 600 to 800°C [8, 9]. Some observers, among them Gold [19], suggest that the smooth areas within the maria were not formed by lava flow at all, but by loose material rolling and jumping down from the crater rims under the action of meteorites and of seismic activity and slowly filling up the craters and lowlands. In this case, however, it would be difficult to explain why impact craters on the maria always appear white against a dark background. They are certainly covered by pulverized material. It would seem unlikely, then, that the black

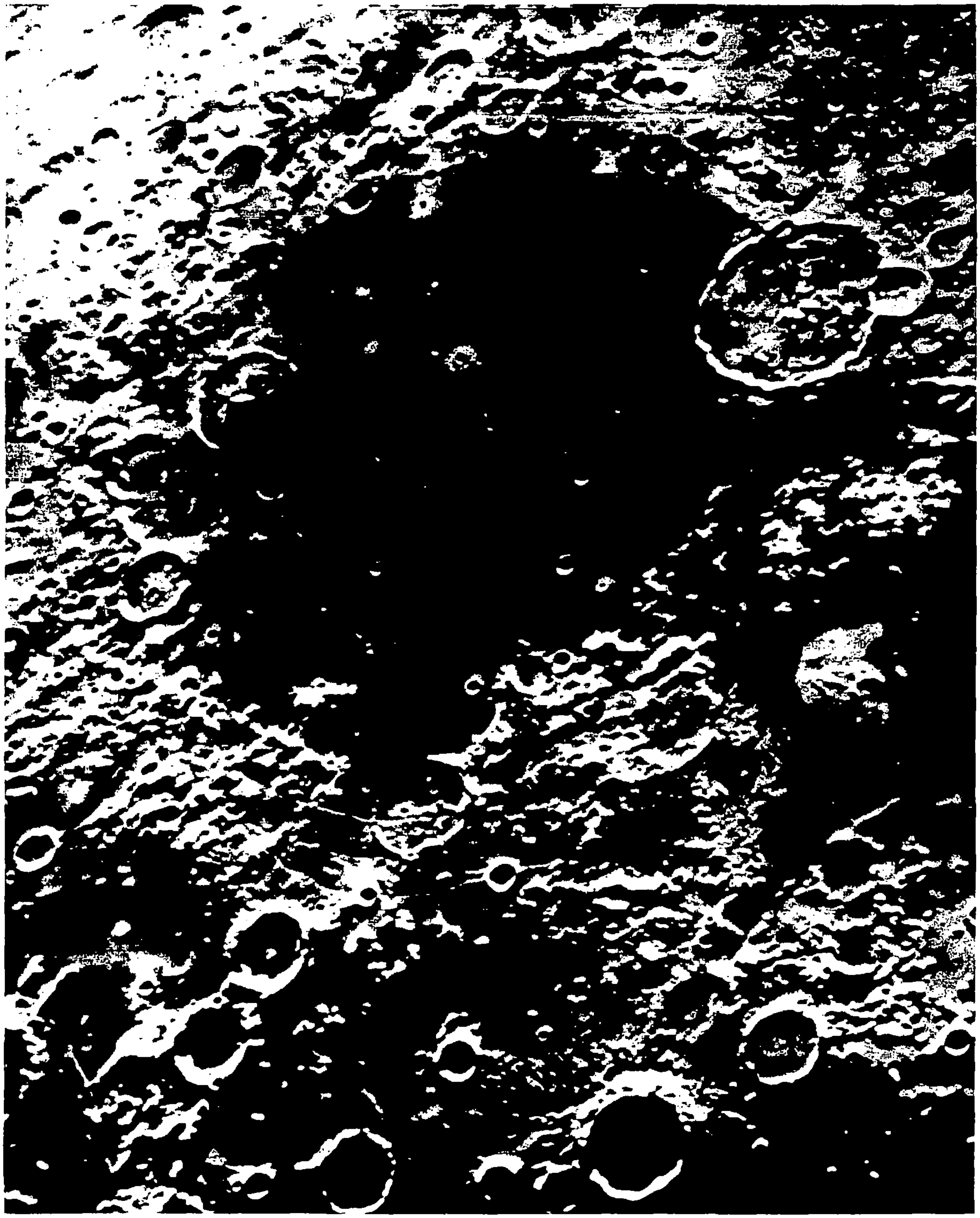

FIGURE 13. MARE HUMORUM WITH CRATER GASSENDI (SOUTHWEST SIDE OF LUNAR DISK)

maria also consist of pulverized material. It is quite probable that the problem of the origin and the nature of the maria will not be solved before on-the-spot investigations are made by human observers.

Another conspicuous feature on the lunar surface which has defied explanation so far is a system of white rays which is found around some of the youngest craters. Tycho, Copernicus, Kepler, Aristarchus, Theophilus, and a few others are known for their bright rays which are very clearly visible at full moon, but invisible under other conditions (Figs. 9 and 10). These rays do not cast any shadows; they must be very thin. Their optical properties, which are different from those of the surrounding material, imply that they may consist of fine quartz or glass-like powder which was ejected during the impact which produced the crater. The fact that only the youngest craters show rays may indicate that the moon, during early phases of its active history, had an atmosphere. At that time, the powder jets thrown out during impacts were scattered and dissipated into diffuse clouds that settled uniformly over wide areas of the lunar surface. As the atmosphere disappeared more and more, the jets retained their dagger-like original shape, and they fell down on the surface as well-defined rays.

The existence of water on the moon is another question which probably will be answered only after extended human exploration of the lunar surface has taken place. Water is an abundant product of chemical reactions as they occurred during early phases of the earth's and the moon's history. There is some possibility that large amounts of water are trapped within and between the rocks underneath the lunar surface. It is even possible that patches of ice exist on the lunar surface near the poles of the moon at the bottom of craters and crevices which are never reached by sunlight [20]. Such places will not only retain, but even will accumulate molecules which are in a gaseous state of higher temperatures, and which freeze out when they come in contact with low-temperature surfaces. This effect is well known from vacuum technology where cold traps are used to clean the system of condensable molecules. Crater bottoms which are never reached by sunlight assume a temperature of 100 to 120°K. The vapor pressure of water at this temperature is of the order of 10^{-12} mm Hg, which is low enough to explain the retention, and even the accumulation of ice over long periods of time.

The temperature of the moon's surface varies between about 400°K at the subsolar point to about 120 to 100°K in the shadow. Figure 14 shows the distribution of the surface temperature over the sunlit hemisphere. Of particular interest is the rate at which the temperature drops when a surface element changes quickly from sunshine to dark. Such quick changes occur during eclipses of the moon. The result of temperature measurements indicates that both the heat capacity and

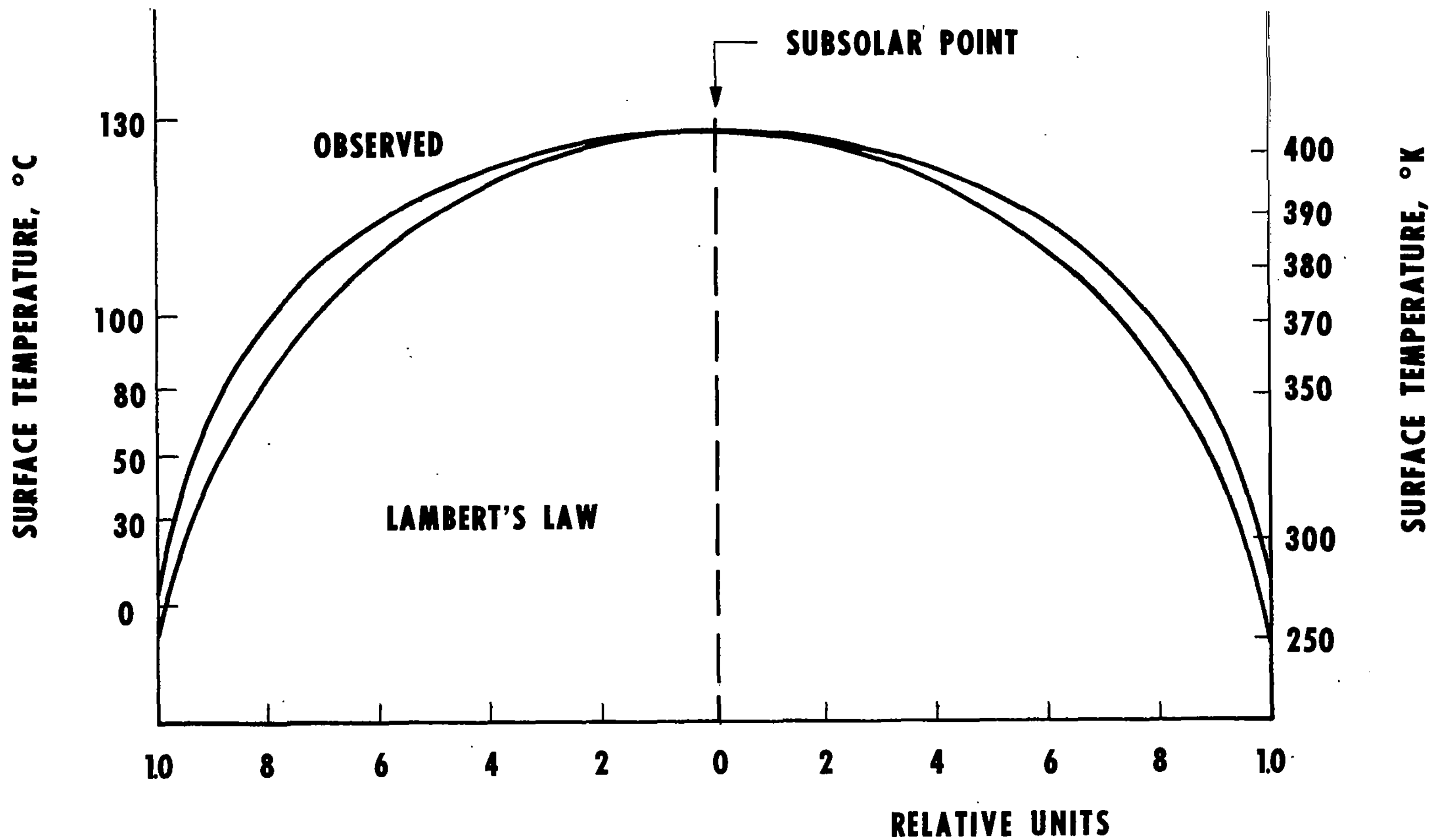

FIGURE 14. SURFACE TEMPERATURE OF MOON

the heat conductivity of the surface layer must be very low; in fact, the heat conductivity is lower than that of any known solid substance on earth [21, 22]. Radar reflectivity measurements in the region of 1 to 10 cm wavelength confirm this conclusion [16]. While the immediate surface temperature follows the day-night cycle rather quickly, the temperatures at about 50 cm and deeper are practically constant. This very low heat conductivity of the surface could be explained by a layer of loose dust or porous material whose particles touch each other only slightly at a few points. The dust could be interspersed by fragments and debris of larger size. The uppermost layer of 2mm, however, seems to consist of very fine dust or a highly porous spongy material with a grain size of only two or three microns as implied by polarization measurements (Dollfus, [23]). Below a depth of about 30 to 50 cm, the heat conductivity seems to be greater. It is possible that solid bedrock, or at least densely packed material, is found from there on down. The finer details of the structure of the lunar surface are unknown. Results of different methods of observation, and of supposedly logical deductions, do not well agree. Radio and radar observations at 10 cm wavelength give the impression that the surface is relatively smooth. This result is surprising, because numerous craters and pits of small sizes, caused by small meteoroids, should be expected. Radar waves between 10 cm and 3 m wavelength, when directed toward the lunar disk, are reflected by a small central region of the disk, implying specular reflection of a spherical surface whose roughness parameter is considerably below the wavelength. The reflection of visual light is particularly interesting. Independent of the angle of incidence, light reflection is always greatest in the direction of the incident light, i.e., toward the source of illumination. This is the reason that the full moon is about 11 times brighter than the moon in the first or last quarter. The illuminated part of the lunar disk is uniformly bright in all phases, which indicates that the reflectivity depends only on the angle between incident and reflected beam, but not on the angle which the surface forms with either one of these beams. Figure 15 illustrates this situation. A similar effect is known on earth when light is reflected from clouds. Flying in an airplane above a cloud layer, one sometimes observes the shadow of the plane on the clouds, surrounded by a bright halo of light. In this case, too, the surface reflects the sunlight predominantly in the direction from which it arrived. This direction coincides with the line of sight of the observer when he looks from the airplane toward the plane's shadow.

This characteristic function of light reflectivity leads to the conclusion that the lunar surface must have a vesicular, very porous structure at a scale of a few microns, or even smaller. It must be pitted by small, but deep holes in all directions. Thomas Gold [24] succeeded in producing such a surface in the laboratory by the extremely gentle sifting of fine particles. The grains, falling down at very low speed, formed a structure which the originator called "fairy

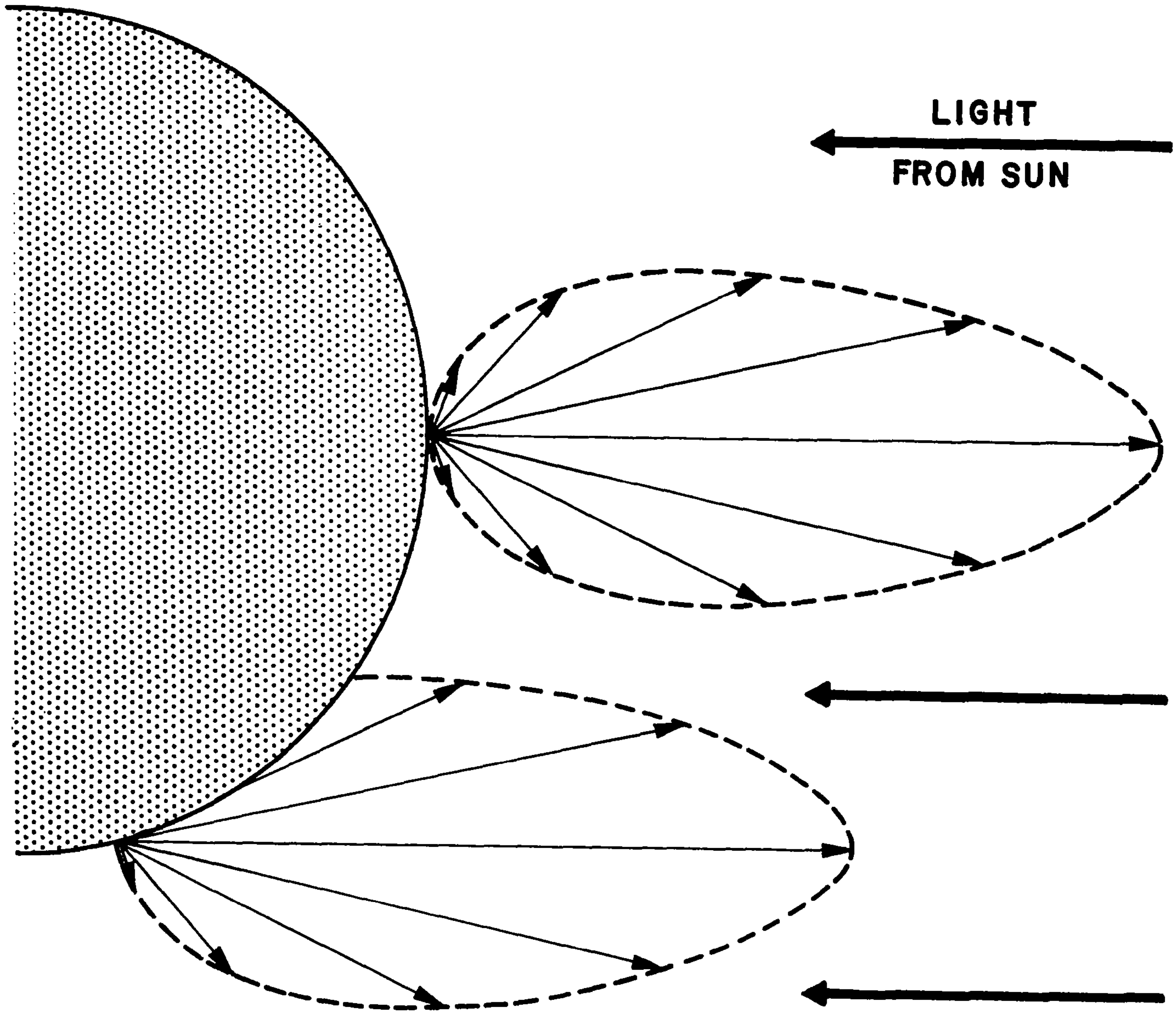

FIGURE 15. REFLECTION OF LIGHT FROM LUNAR SURFACE

castle structure." Although this surface duplicates the optical properties of the lunar surface quite well, it is difficult to understand how such a very delicate structure can be formed by energetic meteorites and their ejecta, and how it can persist under the seismic activities of the lunar surface which are undoubtedly present because of the continuous impact of small meteorites.

Another approach to the simulation of the lunar surface microstructure was taken by Wehner [25, 26]. He exposed surfaces of metal oxides to irradiation by slow protons as they occur in the "solar wind" (several hundred to a few thousand ev energy). After a radiation dose corresponding to several million years of lunar history, the surface showed a highly porous, vesicular structure. The tubes and cavities had dimensions of microns. The optical behavior of the surfaces resembled that of the lunar surface to a surprisingly large extent.

It is interesting to note that infrared light of 8 to 12 micron wavelength does not follow the same law of light reflection. In this light, the lunar disk shows limb darkening, an indication of the fact that the moon's surface begins to approach a specular surface when the wavelength increases.

Kopal [27] pointed out that the moon must have swept up a layer of 60 to 80 cm of cosmic dust during its long period of traveling through space. Again, it is difficult to reconcile this conclusion with the results of optical and heat conductivity observations reported above. Whipple [28] argued that there may be no loose dust on the moon at all, and consequently no cloud to be blown up by the rocket jet of a space craft landing, but that the dust particles are probably all fused and cemented together by "vacuum welding" into a highly porous, froth-like structure.

The question of a lunar atmosphere has been discussed many times. Gases may be produced on the moon either from internal sources where primordial gases may be trapped in rock formations, or by the impact of various radiations that interact with surface materials. Öpik [13] estimated that traces of H, H_2, H_2O, and CO_2 from these sources may be found at partial pressures of 10^{-14} to 10^{-15} atmospheres, corresponding to about 10^5 particles per cubic centimeter. The rates at which the components of a lunar atmosphere would escape from the lunar gravity field can be calculated; Table III contains the time periods required to reduce the partial pressures of various gases to the fraction 1/e of the initial pressures. According to those figures, a CO_2 atmosphere on the moon might be expected. However, as soon as ionization of the molecules by radiation and a positive potential of the moon of 20 to 25 volts as a consequence of photoelectric emission are assumed, even CO_2 will escape in the course of a few thousand years.

TABLE III

ESCAPE OF GASES FROM LUNAR ATMOSPHERE

(Time to reduce partial pressure to 1/e of initial pressure)

GAS	COLD SIDE	HOT SIDE
H	1½hrs	1 hr
H_2	3 hrs	1½ hrs
He	8 days	2½hrs
O	10^{10} years	1.4 years
O_2	10^{26} years	10^{6} years
H_2O	10^{11} years	60 years
CO_2	10^{37} years	10^{10} years

The moon appears to the cursory observer as an absolutely inert, dead body. However, closer scrutiny sometimes reveals slight changes on the lunar surface. Small white clouds, bright patches, mist or haze formations, reddish glow, or even flashes of impacting meteorites have been reported in dozens of cases [29]. One of the better known surface changes in historic times is the disappearance of crater Linné in Mare Serenitatis (Fig. 16). This crater was described by Lohrmann in 1834 as a very deep, well-defined crater of six miles diameter. In 1866, Schmidt observed that the crater was gone, and that only a small, whitish patch remained. It is not certain, though, whether these old observations are reliable enough to permit the conclusion that a substantial change of crater Linné actually occurred. Another very interesting observation of lunar activity was made in 1959 by Kozyrev who observed a gas cloud emitted in Alphonsus crater. Other astronomers confirmed this observation. There were indications that the gas contained molecules of C_2.

In October 1963, a very exciting event was observed from the Lowell Observatory. For several minutes, clouds of an orange color appeared at three different places near the young crater Aristarchus. Presumably, these clouds consisted of a gas such as argon, helium, or water vapor, which was generated a long time ago by radioactive decay, and which had been trapped within the moon's crust until it found a way to escape following some tectonic or meteoric action. The orange color was the result of fluorescence under the irradiation by sunlight.

This short review of our present knowledge, or rather of our present lack of knowledge of our neighbor in space intends to serve as an introduction to the following papers. This review, as well as the papers to follow, will point out one very significant fact: The moon will probably reveal most of its secrets not to the observer on earth, and even not to the observer who orbits around the moon in a lunar satellite, but only to the astronaut who travels to the surface of the moon and explores its features at close distance.

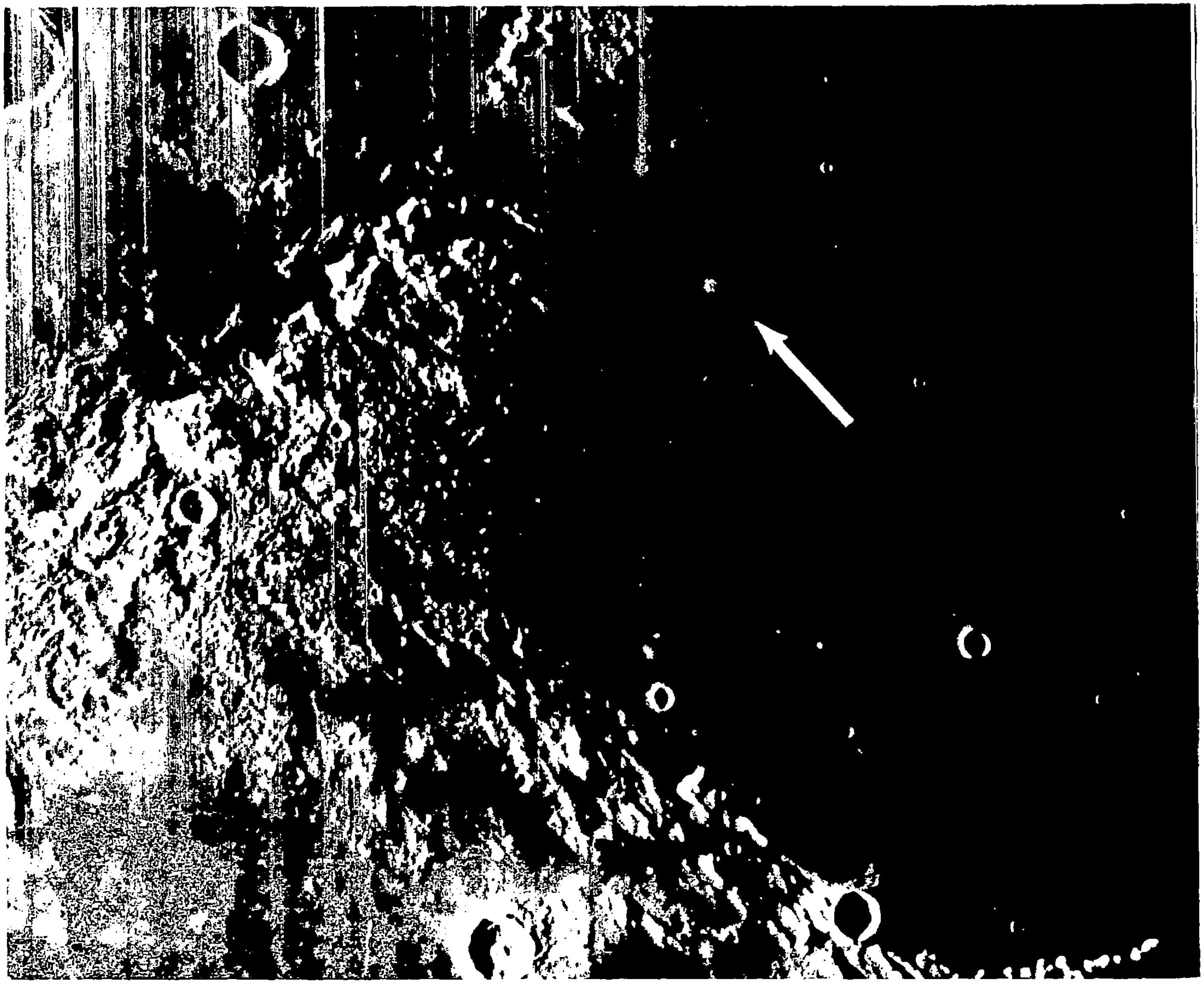

FIGURE 16. MARE SERENITATIS WITH WHITE PATCH LINNE, A WELL-DEFINED CRATER IN 1834

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Chapter 2
PHYSICAL CHARACTERISTICS OF THE LUNAR SURFACE

By

John Bensko *

INTRODUCTION

In the preceding chapter, the possible origin of the moon and its history were introduced. The subject of this chapter is intimately related to these topics. Fortunately one can see the moon's surface to some degree, and by an interpretation of its physiography, one can arrive at some explanation of its history. The moon also lends itself to study by instrumented astronomical techniques. These techniques, despite their inherent weakness as tools for geologic study, provide additional guides toward an interpretation of the nature of the moon's surface.

This chapter has two purposes: (1) to introduce the reader to a short review of lunar surface features and their classification and (2) to discuss briefly the possible condition or nature of the lunar surface material as evidenced from both geological and astronomical studies.

RECENT ADVANCES IN SELENOLOGY

By far the most interesting development in lunar geology recently has been an increasing amount of evidence pointing to a more active moon than had generally been accepted. This has led to a more widespread acceptance of the idea that internal activity exists on the moon even today. Such a state of affairs, if true, indicates a greater possibility for the eventual existence of a self-sustaining lunar base. While not all selenologists agree on the interpretation of recent observations or on the value of laboratory findings, a definite change in the concept of the moon is presently in the making. This change in concept has come about because of several developments; among these are the repetition of luminous phenomena of the type observed by Kozyrev in Ptolemaeus a few years ago and the recent sightings of color changes in the region of Aristarchus reported by the observers at the Air Force Aeronautical Chart and

* Special Projects Office, Research Projects Laboratory

Information Center and substantiated by others. In addition to the efforts toward the search for luminous areas, which may be interpreted as evidence of present lunar activity on a rather large scale, there is an increased interest in the study of lunar features, particularly those that are small and have a questionable connection with meteoritic impact. Coupled with these astronomical observations, numerous studies have been made in the laboratory with rocks and minerals at low pressures and temperatures. Today a large portion of the equatorial region of the moon is mapped topographically on three hundred meter intervals. The accuracy of the location of lunar features or objects is being improved and many subphotographic craters have been located accurately by visual observation.

There have been some disappointments in the quest for new knowledge, however. There is a definite limitation to the usefulness of earth-based astronomical data for the determination of the nature of lunar materials, the moon's structural make-up and small scale features. An extremely important approach to the lunar problem has been the study of hypervelocity impact features and the analysis of the debris arising from impacts in laboratory experiments. These studies will tell a great deal about the debris strewn over the surface of the moon. In addition, the laboratory study of mineral and rock behavior under different environments may indicate the environment-induced changes in mineral matter.

LUNAR TOPOGRAPHY

To the observer, the moon's surface appears pockmarked with large circular depressions and there seem to be two contrasting land surfaces. To Galileo as well as to other early astronomers, these regional differences suggested an analogy to our continents and seas. The term "maria" (seas) used to describe the lunar plains, stems from that interpretation although the terminology has no literal meaning for the moon. Likewise, terms describing familiar earth features, such as mountains, marshes, bays, etc., were applied to lunar features because of their resemblance to the earth's physiography.

Since Galileo's time telescopic observation has allowed the study and classification of lunar objects. Careful determination of their vertical and horizontal extent has permitted a better concept of their physical makeup. Efforts in this direction have, of course, been limited to objects above the telescopic resolution. For a knowledge of the smaller scale features, on the order of a hundred meters or so, a resort must be made to earth-bound analogies.

There is sufficient knowledge of the land formations on the moon's surface to permit a reasonable, tentative classification based on physical appearance. By this criterion, two major physiographic divisions are apparent on the moon's surface. On these regions all other features are superimposed. These are described in Table I.

TABLE I. PHYSIOGRAPHIC DIVISIONS ON THE MOON

Name	Description
Maria (Seas) or Plains	Relatively smooth appearing, dark, irregular to nearly circular lunar regions ranging in size upwards from 300 km Most are interconnected.
Uplands or Continents	Pitted, rough appearing, irregular regions. Remnants occur in maria and are marked by a noticeable increase in the density of craterlets.

The variety of surface relief and markings on the two physiographic divisions can be classified arbitrarily as circular depressions, linear ridges, depressions and faults, and large-scale protuberances in the form of mountains, ridges, and domes. In addition, surface markings in the form of ray patterns are associated with some craters.

The craters present the most conspicuous of all lunar features. By geological definition, a crater is the bowl shaped depression leading into the mouth of a volcano or geyser. By a broader definition, any bowl shaped depressions, regardless of origin, are termed "craters." They are ringed formations on the moon's surface ranging in size below the diameter of maria down to that of the smallest pits. A number of subclasses of craters has been suggested (Table II) on the basis of both size and physical appearance. It is likely that most craters are genetically the same.

Large-scale protuberances on the moon's surface are listed in Table III; linear depressions, fractures, or markings on the moon's surface may be of the types listed in Table IV.

TABLE II. CLASSIFICATION OF CRATERS

Walled Plains:

Large depressions with diameters in the tens of kilometers with little or no wall above the surrounding area and having generally smooth floors. Found only in the uplands. The crater walls appear to be aligned with large fractures that can be traced into the surrounding region.

Ringed Plains and Flooded Ring Plains:

Craters with high walls above their surroundings whose state of maturity has been obscured by a filling of their floor. Where the flooding is extreme and the walls are distorted and/or broken, the craters may be referred to as flooded ring plains.

Impact Craters:

Large depressions in the moon's surface, ranging in diameter down to ten kilometers. When not eroded, the craters have high walls above their surroundings, and exhibit a hummocky relief around the rim. In addition they exhibit a pronounced ray pattern and secondary craters.

Craterlets:

Small circular depressions, 2-10 km in diameter with steep walls. Central peaks are not as evident as in the larger craters.

Crater Pits:

Shallow, circular, or irregular pits up to a few kilometers in diameter lacking prominent external walls.

Miscellaneous:

(1) Small structures resembling terrestrial volcanoes with steep conical hills on which minute orifices exist.

(2) Secondary depressions radial to impact craters.

(3) Large craters with central area completely filled.

(4) Small chain craters with no discernible rim.

TABLE III. LARGE PROTUBERANCES ON LUNAR SURFACE

Mountains:

Lunar mountains are characteristically associated with present or ancient maria and form a part of the rim or wall for these features. Although lunar mountains are high (up to 7600 meters) their mean slopes, like the slopes of larger craters, are low.

Ridges:

Long, sinuous, low elevations found on the lunar plains. Height up to 200 meters, width 2-20 km, length up to a few hundred kilometers.[1]

Domes:

Inverted saucer or elliptical shaped protuberances found in some places on the surface. The formation of domes on the earth's surface may result from a number of causes but only a few might be applicable to the moon.

[1] In addition some of the remnants of crater walls are termed "ridges." These should be distinguished from the "wrinkle" ridges.

TABLE IV. LINEAR DEPRESSIONS, FRACTURES, AND OTHER MARKINGS

Rills (or Rilles):

Narrow (up to 2-km) crevices which appear to be tension cracks on the mare floor.

Clefts:

Long, large grooves, formerly classed with rills, but having a larger width and V-shaped or gently sloping walls.

Faults:

Landslips, or displacement of the surface. Large faults are rare. Most prominent fault is a displacement in Mare Nubium (Straight Wall).

Rays:

Light-colored bands radiating from certain lunar craters. Surface markings with no appreciable height radiating from certain lunar craters. Particles making up the lunar rays are thought to be (1) finely pulverized debris ejected at high but less than escape velocity from the craters and, in addition to this debris, large numbers of small secondary craters oriented in the direction of the ray; (2) disrupted surface veneer whose optical properties differ from the underlying material and which has been disrupted by ejected debris or from radial shock during impact.

In addition to a classification of lunar land forms based on their physical description, other classifications have been suggested that are based on their apparent age and/or origin. While it is doubtful that any classification based on any but the most simple criteria will remain long after a detailed exploration of the moon, these groupings provide a working base for initial studies in lunar geology. Admirable efforts have been made with limited resources in this respect by the United States Geological Survey.

In regard to a classification of lunar features by age or maturity, the craters lend themselves quite well to this treatment. A crater may be described as being "new," "mature," or "old" depending on the apparent condition of its structure. For instance, a "new" crater can be characterized by the presence of a vivid ray pattern, a complete rim, and a sharp hummocky outer slope, and it could include a floor with no apparent secondary disturbances. A "mature" crater, by the same ground rules, will have lost its ray pattern, and the wall and floor might be modified to some degree. An "old" crater will have neither ray pattern nor sharp hammocky slopes on its outer rim and its floor will be characterized by changes including the presence of rills, craterpits, and chain craters. To give specific examples of craters in each of the maturity groups, the "new" crater may be represented by Aristarchus, Tycho, Copernicus, Kepler or any of the bright rayed craters. Copernicus and Kepler are shown in Figure 1. Aristoteles, Bouillaud and Eratosthenes are examples of well known craters which can be placed in the "mature" class, whereas Gassendi and Posidonius may be considered excellent examples of "old" craters. Bouillaud, a mature crater, and Gassendi, an old crater are shown in Figure 2.

A classification of the moon's surface features according to their probable origin is more subjective than the previous classification and it is unlikely that this manner of grouping will be acceptable prior to actual verification during the manned lunar program. The impact hypothesis has generally been accepted as the explanation for the existence of the majority of the lunar depressions. While this is in general acceptance, there are a number of lunar surface forms which appear to have their origin through indigenous lunar processes. This group includes the very large depressions in the lunar uplands which appear to be collapsed sections of the moon's outer skin. The boundaries of some of the present maria also seem to be the result of the moon's internal readjustment rather than being due directly to impact. In addition, many prominent lunar surface features on the present day lunar plains seem to be caused by local or regional subsurface action. On this list can be placed the faults or scarps around the maria, the Straight Wall, the lunar fracture system prominent in the region of Ptolemaeus, the large rills, and possibly some of the lunar domes.

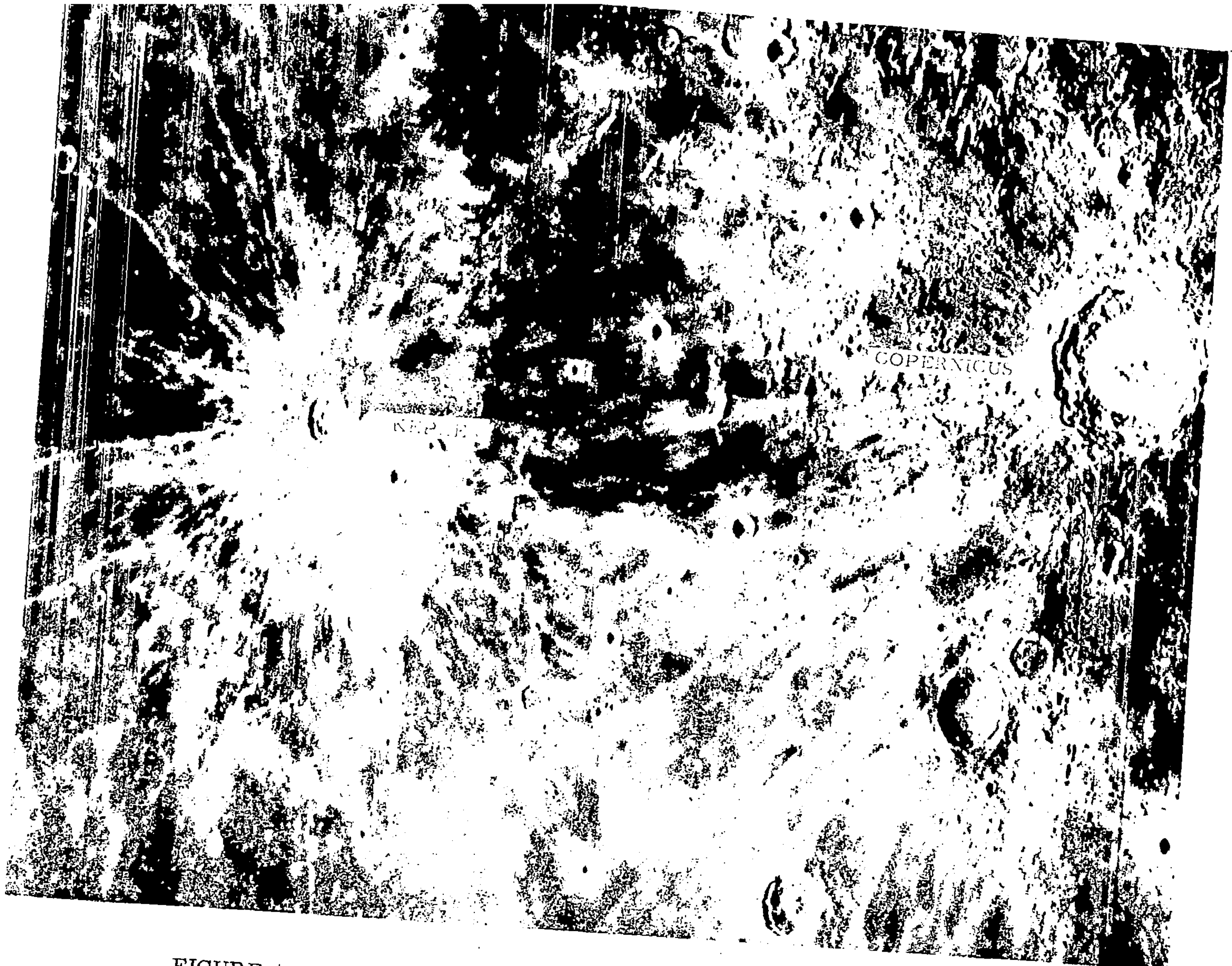

FIGURE 1. EXAMPLES OF "NEW" CRATERS, COPERNICUS AND KEPLER

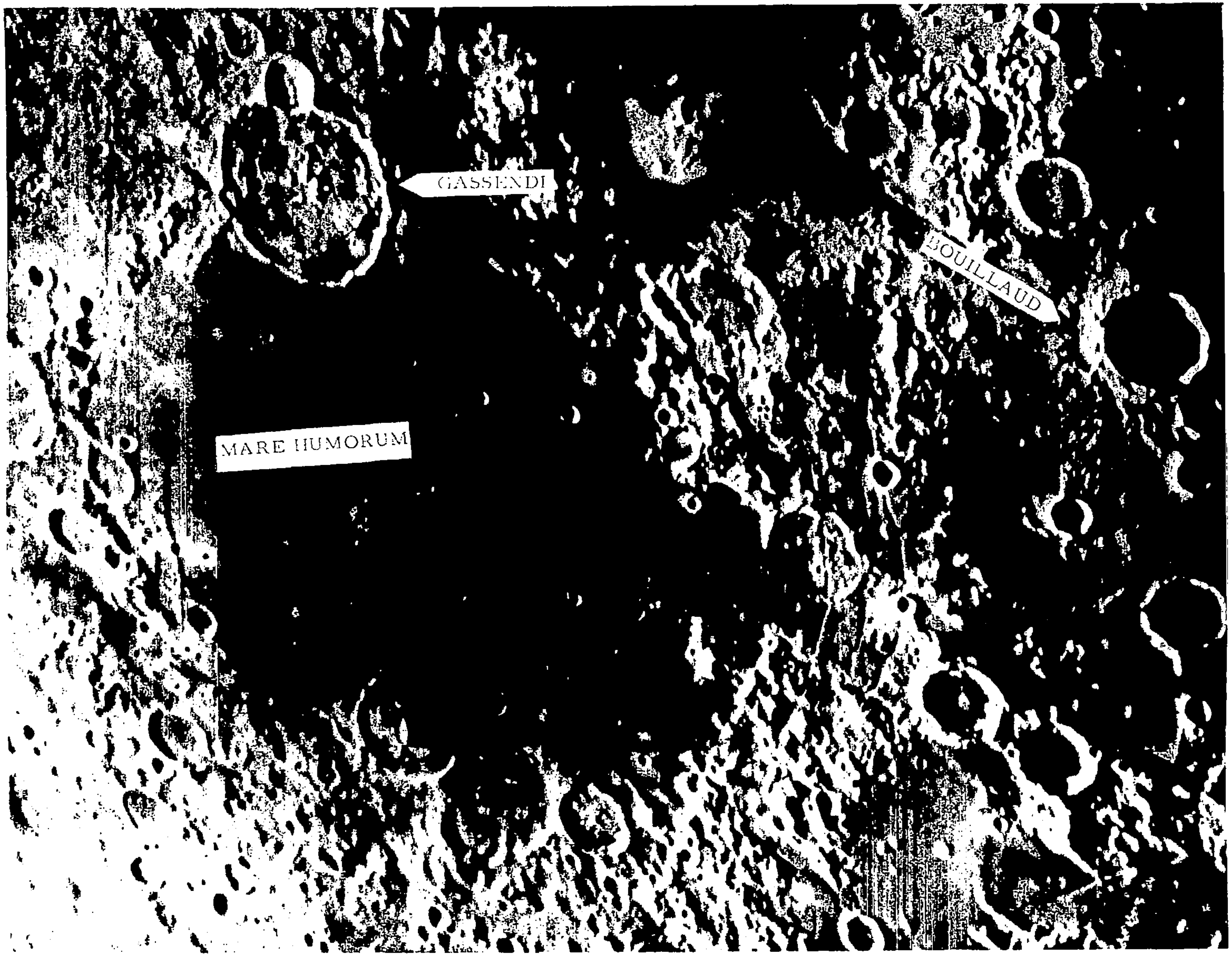

FIGURE 2. MARE HUMORUM, SHOWING EXAMPLES OF A MATURE AND OLD CRATER IN THE SAME REGION

NATURE OF THE ERODED LUNAR SURFACE

The present state of the moon, resulting from its initial make-up and subsequent modification by both endogenetic and exogenetic processes, has been the subject of intense debate for some time. While the question may not be completely resolved prior to an actual lunar landing, some concept of the present conditions on the moon's surface and subsurface may be obtained by recourse to data from a variety of investigations. These are, for example:

a. From studies of the earth: Data from the study of the earth's interior, deformation of the earth's outer regions, composition of the continents and ocean floors, heat flow to the surface, radioactivity of the crust, and processes of erosion and deposition may be used. These data provide some experience concerning the physical and chemical processes of the earth and the extent to which these might be applied, with modification, to the moon.

b. From the chemistry and mineralogy of the meteorites: This study can provide information about rock material from bodies in space other than the earth, i.e., a direct view of non-earth mineral assemblies. This information indicates whether or not all of the earth's mineralogy is unique, or whether it is also possessed in part by other celestial objects.

c. From comparative studies of elements in the sun, the earth, and its crust, and in meteorites: Data from these studies provide information useful as a guide when considering the lunar composition as compared to that of the earth.

All aspects of the character of lunar surface material are shaped by the forces present in its environment. Whatever its initial condition may have been, many processes could alter the original character of the moon's surface material. For instance: (1) surface alteration may come from internal processes, such as (a) deformation in the interior, (b) volcanic type activity on the surface, (c) differentiation or upward migration of elements; or (2) the surface alteration may come from external sources such as (a) cosmic debris, (b) solar and cosmic radiation. These processes can influence the modes of erosion and deposition of materials on the lunar surface and the mass movement of materials and can lead also to major or to superficial alteration of the surface rocks. Some of the processes may lead to changes in the composition of the surface zone. The impact of cosmic debris, for instance, leads to a mixing of rocks all over the moon so that the entire lunar composition may be represented in a local pile of debris. In addition, any of these processes may bring about an increase or a deficit of certain chemical compositions or bring about the formation of new minerals differing from those in an unaffected subsurface zone.

There is often the temptation to view the moon's surface as a vast expanse of homogeneous rock material, marked here and there with craters and crevasses. Indeed, even the earth-based astronomical measurements tend to further this belief in the sameness of the moon's surface rock. If this were really so, it would be completely alien to our experience with rock on the earth. If there is a single similarity between earth rocks, it is that they are indeed a collection of heterogeneous objects. However, the mixing of original heterogeneous materials may be more prevalent on the moon than on the earth. If the impact mechanism is the dominant mode of erosion and deposition, then the debris from all surface regions of the moon may have been mixed, thus forming a homogeneous veneer covering a heterogeneous subsurface.

While the moon has often been referred to as a relatively inactive body which may have preserved a very ancient relief for inspection, it is readily apparent that very little of the moon's surface veneer has been left undisturbed during its history. Those erosion agents common to the earth, viz., water and atmosphere, working against the efforts of active internal forces, are absent on the moon. The destructive action of cosmic debris impacting on the moon, however, constitutes a very strong and active erosion agent. On the earth, the internal forces, along with the erosive action of water and air provide the earth's surface with a physiography peculiar to its erosive history. The surface relief of the moon, too, is dominated by the results of the action of its erosive agent, cosmic debris. The effect of cosmic radiation is not certain, but sputtering action may have provided a mechanism for the removal of some centimeters of material. The thermal breakdown of lunar rock material might have been another erosion process on the moon at some time in the past. The presence of moisture seems to be an essential agent in this action, which precludes its occurrence at the present time.

In studies of earth-bound rock material, the character of surface rock may be expressed in terms which describe its physical and chemical condition. Thus, if a rock type is made up of grains of material, its character may be expressed by:

(1) its composition
(2) the sizes of the particles making up the aggregate
(3) the geometry or shape of the grains
(4) their density or compaction cementation and packing arrangement.

The composition of a rock unit is derived from the mineralogy of the parent rock or rocks making up the detrital material while the physical character is influenced by both the condition of the parent rocks and the environment of erosion and deposition.

Rock debris being transported by or through our atmosphere is generally well sorted. Selection is made upon the basis of density, mass, size, shape, and uniformity of the particle and the wind velocity and density of the atmosphere. The impact debris in the vacuum environment occurring at the lunar surface will be poorly sorted and those particles which rejoin the surface will not be well graded.

Figure 3 illustrates schematically the major differences in the earth-moon "soil" profile due to the mode of origin and weathering history. Rock fragments in either case are influenced by their environment. On earth very little of the surface debris is derived from meteor impact, whereas, on the moon this appears to be a dominant erosion mechanism. The mode of breakage itself provides, on the moon, a more irregular fragment. This difference in shape is heightened by the subsequent weathering and abrasion from wind and water on the earth.

The terrestrial atmosphere, with its gaseous atmospheric components along with water vapor, has a pronounced effect upon the interaction of solids and granular materials. Windborne material abrades the surface of rocks and water grinds and polishes them. The particles are surrounded by films of water vapor and absorbed substances preventing clean surface interparticle contact. In the earth's gas-rich environment chemical cements form a matrix to bond granular particles together. The rock mass, if derived from primary rocks, is altered chemically by selective enrichment from the weathering-cementing process. The lunar detrital zones must rely on sputtering action from radiation bombardment or the escape of volatiles in the vacuum environment for secondary changes in their chemistry.

It is very unlikely that any clastic material will remain unattached to other rock surfaces for any length of time. Mechanical interlocking, vacuum and radiation bonding of granular materials have been demonstrated in the laboratory. There is the possibility of rock grains being mechanically or electrostatically held together without becoming a rigid structural unit. The degree and the time that such agglomerations may exist is uncertain.

Dendritic arrangements of clastic material are more likely to occur on the moon with its lower settling velocity and high vacuum. A dendritic structure composed of clastic material from the impact process is shown in Figure 4. A similar appearing fibrous or whisker texture may arise from radiation bombardment and from chemical growth.

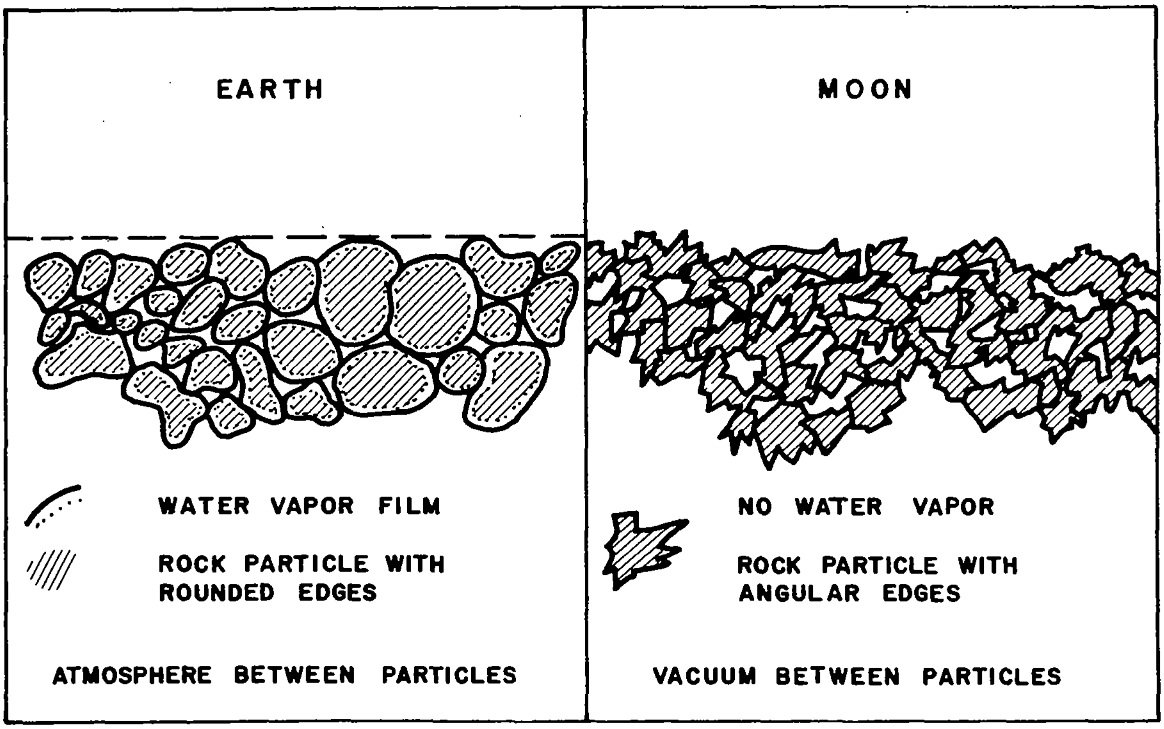

FIGURE 3. COMPARISON OF "SOIL" PROFILE WITH EARTH AND LUNAR CLASTIC MATERIAL

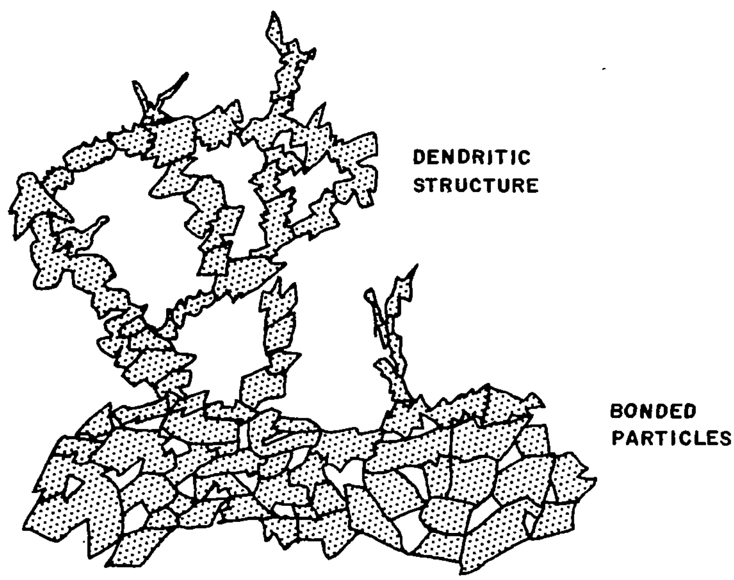

FIGURE 4. GROWTH OF VACUUM BONDED PARTICLES OF CLASTIC MATERIAL SHOWING DENDRITIC STRUCTURE

In addition, melted material, if gas rich, will provide an extremely porous rock structure on extrusion from the subsurface to the high vacuum environment. The presence of frothy and dendritic clastic materials should not be rare on the moon since the environment is quite able to allow the formation of these structures. (Figure 5)

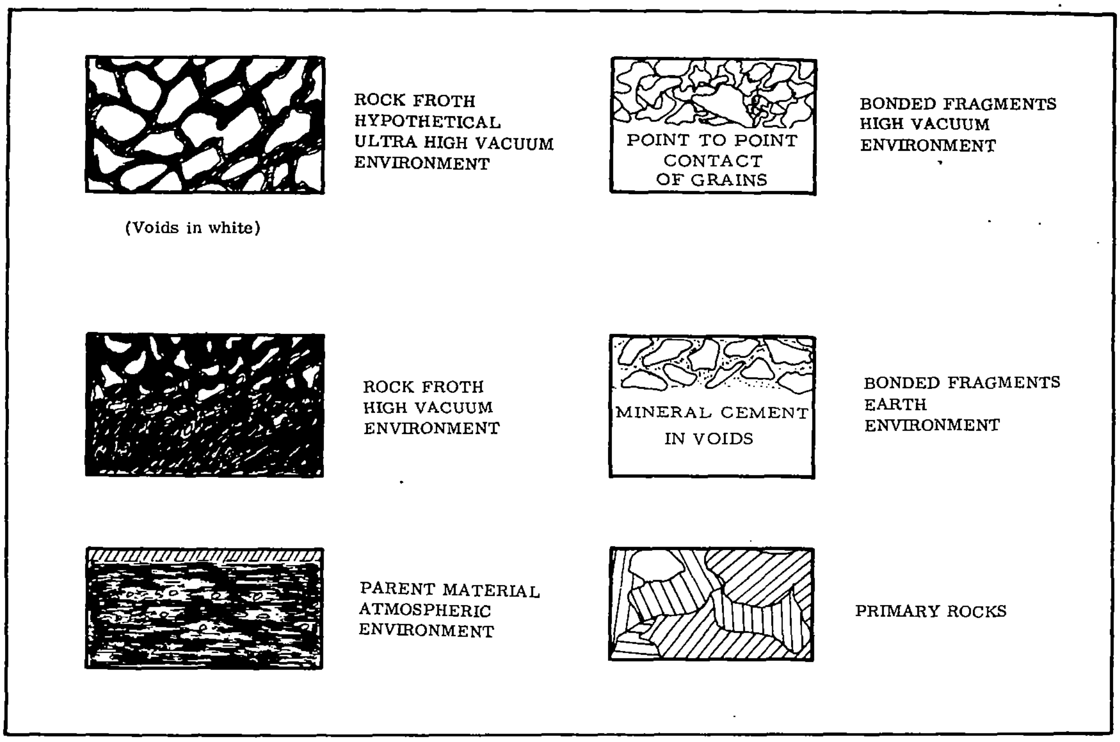

FIGURE 5. TYPES OF LUNAR SURFACE MATERIAL

The presence of impact debris in several degrees of consolidation has been generally accepted as the reasonable surface material on the moon. The acceptance of lava flows in the form of froths and degassed lava sheets has not been so readily attained. Perhaps this is due to the lack of obvious geological activity on the moon's surface.

It is difficult to detect geologic processes taking place on the earth on a large scale in a limited period of time. But a number of changes on the moon, however small, are significant when discovered. Several locations on the moon's surface have indeed changed some aspects of their appearance during observation; this has been confirmed by more than one observation. Other changes, although they may be important, have been reported only on the basis of a single observation.

Those locations on the moon where changes of significance have been observed by more than one observer during the brief few hundred years of observations are as follows:

Alphonsus
Aristarchus
Herodotus Valley
Linne
Messier
Pichard
Plato
Schickard
Tycho

Apparent changes in these nine locations have been reported during the last century. Whether any of the observed "changes" involve an important geologic disturbance is questionable. The descriptions of the observers, if correct, lead to the conclusion that easily volatilized elements are still escaping intermittently from the moon in restricted locations.

With a relatively inactive planetary-size body, as is the case for the moon, external activity is generally assumed to play the dominant role in both the origin and evolution of its relief. Perhaps a secondary contribution is provided by internal causes although the magnitude of such action is apparently small compared to that provided by the former. The concurrent building and modification of lunar relief by the random bombardment of cosmic debris and the secondary products after impact are the dominant agents influencing the lunar topography.

By far, the dominant topographic object influencing the surface configuration is the crater. The larger of these on the maria have rather gentle slopes on their outer rims. The smaller craters are likely to possess low slopes on the outer rim as well. The degree to which crater relief dominates the surface varies from region to region. Crater density is greater in the uplands than it is in the maria, the former region being exposed as a target to cosmic debris for a greater length of time. Crater density also increases in proximity to a large, unaltered crater where the pits formed by secondaries are still intact. In some areas of the maria, the surface appears relatively free of large craters.

The moon's surface does not become infinitely rougher because of the increase in influx of the smaller cosmic debris. This seems to be so even though smaller craters are in the majority. The number of steep-wall small craters may be diminished as a consequence of the impact process itself.

Succeeding impacts of cosmic debris lead to the modification or destruction of crater forms on which they impact. Such a process would have a degrading effect on the larger craters. On smaller craters this action would lead to a complete modification of the crater shape. Leveling action caused by the shock generated from meteorite impact with the moon's surface coupled with fine debris scattered as a result of mechanical breakage of lunar material, should also lessen the hazard from holes resulting from the presumed greater influx of smaller particles. Perhaps even a more important source of leveling is the debris ejected by the craters. While estimates on the thickness of such cover material vary, any thickness should decrease the roughness introduced by impact.

What is known presently concerning large blocks of rock debris is obtained indirectly by earth-bound study of crater debris and by interpretation of the visible appearance of the region around craters on the moon. The extent to which the character of debris around earth-bound craters resembles that associated with a similar feature on the moon is not certain. For those earth-bound and lunar craters formed in solid rock material at least some similarity is associated and may be assumed--given the same initial conditions of impact. The presence of an atmosphere around the earth-bound crater may help to concentrate material around the crater and influence the sorting of the sizes of debris associated with the crater rim. It seems, then, that the maximum block size associated with earth-bound craters in solid targets can only indicate an upper limit for the size of impact or explosion debris associated with lunar craters. Targets of weak, foam-like structure will likely provide a better analogy to the lunar impact process.

In summary, the environment and the conditions of erosion on the moon should lead to highly irregular fragments of rock debris. Rock in this condition, despite the apparent lack of common earth-type erosion processes, is influenced by radiation and micrometeorite bombardment. The net effect of radiation, provided enough exposure time is available, is to cement the particles, to change the optical properties of the material, and to effect some chemical changes (e.g., the removal of oxygen for certain oxides). The effect of micrometeorite bombardment is to break down the large scale irregularities in surface topography and to increase the textural or small scale irregularity of the rock material.

The rock material comprising the moon's surface is largely derived from native lunar materials rather than from the later accumulation of cosmic debris. This material is composed of fragmented rock from explosions and of extruded material from the moon. Its texture and geometry on a small (textural) scale should be extremely rough whether it is derived from plutonic or explosion sources. While much of the debris in any area is derived from the local subsurface, perhaps half or more will be derived from all sections of the moon.

In regard to lunar surface geometry, as the scale of the surface geometry is increased, the moon becomes smoother. Thus, at optical wavelengths, the moon is rough, but on a scale of tens or hundreds of meters, the moon becomes smooth. The percentage of surface covered by meteor scars or crater pits visible from the earth is only a small part of the total surface in the maria. The spatial distribution of these craters varies, but for the Ocean of Storms, for instance, they cover less than 10 per cent of the surface. In the case of the uplands, the overlapping of even the larger craters suggests that all of the topography is made up of crater forms.

Chapter 3
THE LUNAR ATMOSPHERE

By

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The lunar atmosphere is so tenuous that for all practical purposes it is non-existent. Since it is equivalent to a vacuum attainable on the earth only with extreme difficulty and by the most refined techniques, one might question the need for examining it to any great extent. Yet, as will be seen below, the presence of such an atmosphere may play an important role in determining certain physical phenomena and may provide significant clues concerning the moon's history.

Because of its tenuity, lunar explorers will have to take along their own atmospheres in space suits, for breathing and to provide the external pressure necessary to keep the fluids in their bodies from boiling and to keep them from literally exploding. The atmosphere will not provide braking for a spacecraft landing on the moon, nor will it provide lift for flights from one point to another on the lunar surface.

Early man, observing the moon in the heavens, ascribed to it the same environmental conditions that he observed on the earth, a similar atmosphere and large bodies of water (the maria), and assumed that it was populated with plants, animals and people similar to those with whom he was acquainted. The development of the telescope, permitting a closer look at the surface, disclosed conditions of a quite different nature. The maria were shown to be dry, flat plains; the surface indicated neither the presence of water nor a sign that there had ever been appreciable amounts of water, at least, not sufficient to cause erosion features of the type with which we are familiar on the earth. Observations also failed to disclose any appreciable atmosphere.

Studying the atmosphere of the moon, or for that matter the atmosphere of the planets, is not a simple matter. Since these bodies shine by reflected light rather than by incandescent gases, it is impossible to employ the spectrographic techniques used with such success in studying the composition of the sun and distant stars. To date no one has been able to measure the atmosphere of the moon directly. Most of the methods merely establish the presence or absence of an atmosphere. Most of the observations designed to detect a lunar atmosphere

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have failed to do so and much of the discussion of the lunar atmosphere is sheer speculation. Most statements concerning the lunar atmosphere say that it cannot exceed a certain value, which has been limited by the precision of the measurements being made.

Estimates of the density of the lunar atmosphere have been steadily dropping as more refined observational techniques have been employed. The latest, and presumably the most accurate estimates (by occultation of radio stars) indicate a density for the lunar atmosphere of 10^{-13} that of the earth's. Table 1 lists some of the more recent determinations of the density of the lunar atmosphere.

TABLE 1. RECENT DETERMINATION OF DENSITY OF THE LUNAR ATMOSPHERE

AUTHOR OR EXPERIMENTERS	METHODS	MAXIMUM DENSITY OF LUNAR ATMOSPHERE (density of earth's atmosphere at sea level equals 1)
Russel, Dugan and Stewart [5]	Absence of Twilight	10^{-4}
Lipskij [7]	Photography of Twilight in Green Light with a Polarimeter	10^{-4}
Lyot and Dollfus [8]	Photography of Twilight in Yellow Light with a 20 cm Coronograph	10^{-8}
Dollfus 1952 [9]	Photography of Twilight in Orange Light with a 20 cm Coronograph and Savart-Lyot Polariscope	10^{-9}
Elsmore and Whitfield [12]	Refraction of Radio Waves in Lunar Ionosphere	10^{-12}
Costain, Elsmore and Whitfield [13]	Refraction of Radio Waves in Lunar Ionosphere	10^{-13}

Because of such a tenuous lunar atmosphere one may question the need or desirability for so much discussion and investigation. Öpic [1, 2] states that an atmosphere of even this tenuity has an influence on certain environmental aspects. A density of 10^{-13} that of the terrestrial atmosphere still has 10^{13} atoms or molecules above each square centimeter of lunar surface, sufficient to absorb completely certain spectral line emission. This number is near the amount limiting the escape of molecules from the lunar surface directly to interplanetary space. A full-scale ionosphere may develop under these conditions and the electrical conductivity thereof may have an influence on the charge of the lunar surface and even on the behavior of dust particles.

With the present objectives of space exploration it is even more important to determine not only the amount of lunar atmosphere but its composition as well. Such information would be of value in determining the past history of the moon as well as its present environmental conditions. These composition measurements will probably be delayed until an instrument package containing a mass spectrometer or similar device can be placed upon the surface of the moon. Studies are now being made to develop flight model mass spectrometers for the analysis of the lunar atmosphere and surface. But until such time as these instruments, or similar ones, are in actual operation and providing usable information, recourse must be made to other methods for establishing the presence or absence of an atmosphere. Methods of determining the lunar atmosphere and some of the results obtained are discussed by Fielder [3] and Baldwin [4] in recent books on the moon.

The present optical, spectral and radio techniques which are available for detecting or estimating the amount of atmosphere on the moon are described briefly as follows:

(1) Optical Methods

(a) Occultation of Fixed Stars. The occultation of fixed stars method uses the observation of the eclipse of a star as the moon passes between it and an observer on the earth. A lunar atmosphere should cause a slight haziness as the star disappears behind the moon and reappears on the other side. Likewise refraction of light by an atmosphere should reduce the time of occultation slightly from theoretical.

(b) Deviation of Lunar Limb from Perfect Circular Shape. A slight deviation of the lunar limb from a circular shape should be observed if a lunar atmosphere is present.

(c) <u>Twilight Arc.</u> H. N. Russell [5] has pointed out that lunar atmosphere illuminated beyond the terminator should be visible if the density were of the order of 10^{-4} to 10^{-5} that of the terrestrial atmosphere.

Since none of these methods has given what might be considered as positive results, Öpic [3] placed the upper limit of the lunar atmosphere at 2×10^{-7} of the terrestrial atmosphere.

Lipskij [6, 7] thought that an observation of an occultation of Jupiter made in 1889 indicated that a lunar atmosphere was present. Öpic [3] thinks that it was chromatic aberration in the telescope that was observed. Lipskij in a recent detailed observation of polarimetric observations arrived at a value of 1/12,000 that of the terrestrial atmosphere. Since this is some 50,000 times greater than values obtained by Dollfus and his co-workers [8, 9] Öpic expresses grave doubts as to the accuracy of Lipskij's results.

Haas [10] and La Paz [11] thought that they observed meteor trails on the moon, indicating some atmosphere, but these have not been substantiated.

(2) Spectral Methods

Spectral methods are complicated by the fact that the substances to be observed in the lunar atmosphere are also in the terrestrial atmosphere and it is difficult to distinguish between them. The moon does not change its position relative to the earth sufficiently to permit line shifting due to the Doppler effect such as has been proposed in studying the Martian atmosphere.

(3) Radio Observations

Occultation of the Crab Nebula has been observed by radio methods by Elsmore and his associates [12, 13]. They have estimated the lunar atmosphere to have a density of 10^{-13} that of the earth. This is the most generally accepted value at the present time. Some observers consider this to be an upper limit and that the actual value may be lower, while others think that this method, which measures the electron density, may be low if argon, with a high ionization potential, is the chief constituent of the lunar atmosphere.

Estimates of the amount of the lunar atmosphere based on the kinetic theory and the past history of the moon indicate that only a slight atmosphere is to be expected. The kinetic theory of gases restricts the presence of gases in planetary atmosphere to those whose root-mean-square velocity, V_m, is a small fraction of the escape velocity, V_{esc}. Jeans [14] has found that an atmosphere will be stable for astronomical periods (10^9 years) if V_m is about one-fifth of V_{esc}. His calculations have been modified by Kuiper [15] for denser atmospheres, but for one as rarefied as that on the moon, the method of Jeans will suffice. Jeans calculated the escape velocity on the moon to be 2.40 Km/sec, in which case only those gases with a velocity of less than 0.48 Km/sec could survive on the moon. On the assumption that the rate of escape of gases is determined by the maximum temperature of the surface, 370° K, only gases with a molecular weight greater than 60 could be expected to remain as an atmosphere. As will be seen later, there is some possibility that gases will condense on the colder portions of the moon and that the temperature there, rather than at the hottest areas, will be the governing factor.

It is to be expected that the lunar atmosphere should consist mostly of argon with xenon, carbon dioxide, sulfur dioxide and possibly water vapor present. They might exist partly as a lunar ionosphere. However, according to Herring and Licht [16] none of these gases are to be found in the concentrations postulated by theory. Water vapor would be decomposed by ultraviolet radiation into hydrogen and oxygen; oxygen would escape much more rapidly than would water itself. It is also assumed that the other constituents would be ionized or decomposed and thus escape more readily. If, as assumed, the moon has a positive charge of 20 volts, ionization of even the rare gases, xenon and krypton, to positive ions would produce a repelling force sufficient to cause them to escape more rapidly.

It is generally assumed that the terrestrial planets lost the original gaseous envelopes acquired in the process of their formation, and that their present atmospheres evolved later, after solidification of the crust and subsequent cooling permitted the retention of an atmosphere. While Urey [17] does not believe that the moon was ever in a molten state, it was probably at a temperature which would cause the loss of any original atmosphere. The present atmosphere then would be the result of a balance between the rate at which a gaseous layer was being formed and the rate at which it was being lost.

Edwards and Borst [18] have discussed several possible sources of the heavy rare gases, krypton and xenon, which are thought to be too heavy to escape from the lunar surface. Some of these sources are: spontaneous fission of uranium-238, fission of uranium-238 by thermal neutrons from cosmic rays, thermal fission of uranium-235 from the reaction 0^{18} (α, n) Ne^{21}, xenon production from iodine-129, and from primeval gases trapped in rocks. Based on comparisons of the earth with the moon, they conclude that three mechanisms appear adequate to account for the amount of atmosphere predicted by the radio astronomy observations of Elsmore and his co-workers. These mechanisms are the spontaneous fission of uranium-235, xenon-129 from iodine-129, and primeval gases.

The surface of the moon is generally considered to be quite porous and should contain quantities of trapped gases, which are released by erosions due to meteoric impacts. Heat generated by such impacts may also cause volatilization of some of the gaseous constituents of the rocks themselves. Trapped gases in the meteors themselves may also be released upon impact.

Interplanetary gases as well as some gases escaping from the earth may be collected on the lunar surface. Firsoff [19] attempted to calculate the density of a lunar atmosphere condensed from interplanetary gases and arrived at 10^7 particles per cubic centimeter. Brandt [20] objected to this value and stated that the density of a lunar atmosphere could not be more than a few per cent higher than that of interplanetary space. Firsoff [21] stated that the porous surface of the moon might hold considerable amounts of gas which would be released by heating in sunlight but which would be condensed at night, thus accounting for the low results obtained by Dollfus. Firsoff also points out that if the lunar atmosphere contains large amounts of argon it may not be highly ionized, and the actual amount may be higher than that obtained by Elsmore in radio observations. Brandt [22] was still not convinced.

Herring and Licht [16] have calculated that if the heavy inert gases accumulate at the rate estimated from terrestrial data, the moon should have a much denser atmosphere than it now appears to have. They argue that some other mechanism than that of normal thermal escape must be operating to reduce the amount of such material in the neighborhood of the moon. They suggest that the solar wind could do so. It is usually assumed that the solar wind is composed of protons with an abundance of 1,000 per cubic centimeter and at a velocity of 10^8 centimeters per second. Such high-velocity protons would transfer sufficient kinetic energy to the atmospheric atoms to permit them to escape from the moon. Herring and Licht have also reported that both hydrogen and argon could be produced in a lunar atmosphere by bombardment of the moon's surface by the solar wind. Helium is also produced by the action of cosmic rays, but because of its light mass would not remain on the moon long. Argon would also be produced by the action of radioactive potassium.

While many of those who estimate the rate of escape of gases from the lunar surface base their estimates on the maximum temperature reached during the lunar day, others say that the estimates should be based on the lowest temperatures found on the moon. Watson, Murray and Brown [23] point out that the amount of any volatile material in the vapor phase, and hence its mass removal rate from the moon, is determined by the temperature of the solid phase at the coldest place on the lunar surface. They have developed a theory of the behavior of volatiles on the lunar surface which takes vapor pressure equilibrium into account, and from it show that water is by far the most stable of the naturally occurring volatile substances that conceivably might have been released at some time on the lunar surface. They also show that the amount of water that could have been removed from the surface since it attained its present conditions is quite small. They believe that the amount of water on the surface should be a large part of that originally present. There are areas on the moon that are permanently shaded and which have temperatures in the order of 120° K. Since these areas are estimated to make up about 0.5 per cent of the lunar surface it would be possible for them to trap considerable amounts of water.

It has also been shown that there conceivably could be a migration of volatile materials across the lunar surface from those areas being warmed by the sun at lunar dawn to the colder areas remaining in the shade. The lunar surface, presumed to be of quite a porous nature and with a low heat conductivity, could retain ice and other volatile materials just below the surface and in areas where the sun's rays do not reach. While such volatiles do not constitute a permanent atmosphere, their presence is of interest as a source of materials for producing an artificial atmosphere on the moon.

While all indications are that the lunar atmosphere is most tenuous, it does appear that at times observable quantities of gases or vapors appear on the lunar surface. While this is still a matter for discussion, observers have noticed certain features of the moon to be obscured as though by clouds of mist or dust, apparently issuing from cracks or fissures in the surface. One of the most interesting of these occurred in the crater Alphonsus in 1956, when Alter [24] observed what appeared to be a haze due to a slight discharge of gas from tiny, very black spots along the rill. On November 3, 1958, Kozyrev in Leningrad observed what appeared to be a gaseous emission in the same area. It also appears that other observers saw a similar phenomenon at about the same time.

Observations of such gaseous eruptions are not too frequent, but then it seems that the moon has been a rather neglected object. Although it is the most conspicuous object in the sky, it had been neglected by astronomers in general until recently, when prospects of space exploration with the moon as the first objective aroused interest in it and caused closer and more careful observations to be made.

It is really surprising how much speculation and how little real knowledge exists about such a familiar object as the moon. The lunar atmosphere is a good example of this. There is still much uncertainty and actual disagreement about the nature and amount of the lunar atmosphere. The only way to answer the questions arising about the atmosphere is to send instruments, manned or unmanned, to the moon and actually make studies and measurements of the surface conditions and the atmosphere.

SUMMARY

In summary one can say that not too much is known about the atmosphere of the moon. Most of the attempts to detect or measure the lunar atmosphere have given negative results and have shown that the moon could not have an atmosphere with a density greater than the limits of sensitivity or accuracy of the methods employed. As the techniques have improved, this value has become smaller until the generally accepted value is that the density is about 10^{-13} that of the terrestrial atmosphere, at least for a permanent atmosphere. Meteoric impacts might generate sufficient heat to liberate trapped gases on the surface.

Trapped gases and vapors may be present on the lunar surface in such quantities that they could be used to produce an artificial atmosphere once lunar bases and facilities have been established; but until this is verified, space explorers should consider the lunar atmosphere to be non-existent for all practical purposes.

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Chapter 4

ENERGETIC RADIATION ENVIRONMENT OF THE MOON

By

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INTRODUCTION

At the present time, of course, there have been no actual measurements made of the radiation environment of the moon, although this situation will likely be remedied within the next few years. The information which will be presented is, therefore, somewhat speculative and subject to constant revision. However, the present information indicates that the radiation environment is not likely to be a critical factor in the early expeditions to the moon. Perhaps the greatest hazard is the possibility of a large solar flare.

The energetic radiation environment of the moon consists of several sources. The most important are the following:

1. Primary Cosmic Radiation
2. Solar High Energy Particles (Solar Flares)
3. Induced Surface Radiation
4. Decay of Naturally Occurring Radioactive Elements

Of secondary importance are high frequency electromagnetic radiations produced in the solar system and solar winds. These will not be discussed.

GALACTIC COSMIC RAYS

Galactic or primary cosmic rays are energetic particles originating outside the solar system. They consist mainly of protons but include alpha particles and stripped nuclei (Table I).

In Table I, it is seen that the hydrogen nuclei, or protons, make up 86 per cent of the cosmic rays, and their flux above 1 Gev is a factor of 10 greater

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TABLE I COMPOSITION AND FLUX OF PRIMARY COSMIC RAYS

COMPONENT	PERCENT OF TOTAL	FLUX (E>1 Gev)/cm^2-YEAR
HYDROGEN NUCLEI	86	3×10^7
HELIUM NUCLEI	13	3×10^6
Li, Be, AND B NUCLEI	0.16	3×10^4
C,N,O, AND F NUCLEI	0.54	8.5×10^4
NUCLEI WITH Z>10	0.19	3×10^4

than all the others combined. The second most important component is that of the helium nuclei or alpha-rays which constitutes 13 per cent of the total particles. Because of the high energy of some of these particles, they are extremely penetrating and are difficult, if not impossible, to shield against. In fact, it can be shown that at some points the dose increases when a shield is added. In Figure 1, the energy of energetic protons in Gev is plotted versus the distance required to completely stop the proton in sand with a density of 2.65 gm/cm^3. Note that for the average energy of the cosmic rays, 4 Gev, it requires 8 meters of sand to stop the proton. The dose rate from galactic cosmic rays in free space is thought to vary from 5 to 10 rads per year over the 11-year solar cycle. Because of this relatively low dose rate and the impracticality of providing shielding against them, galactic cosmic rays are not likely to affect the design of radiation shields on the moon or the design of space ships. However, there are some scientists who believe that the highly localized energy deposition produced by a heavy particle slowing down in a sensitive organ of the body might cause damage much greater than the presently calculated dose rates. For this reason the following information is provided.

The energy range of cosmic ray protons extends from less than 100 Mev to greater than 10^{12} Mev. The average energy of all the particles is about 4 Gev/nucleon. The energy spectrum of the cosmic ray protons is shown in Figure 2. This figure also shows a solar flare proton spectrum based on a six-year average from 1956 through 1961. The solar flare protons will be discussed later.

In free space, the galactic cosmic ray flux is usually assumed to be isotropic in direction. In the vicinity of the moon, however, the moon itself provides partial shielding as does the earth in regions of space close to it. The atmospheric and magnetic fields of the moon, however, are so negligible that they offer no protection such as that afforded to the earth against charged particles.

In Figure 3, the minimum energy in Mev of protons that can arrive on the lunar surface at the equator is plotted as a function of a variable surface magnetic field, in Gauss, that may be found at the magnetic poles of the moon. If the moon has a polar field of 10^{-2} Gauss, considered to be an upper limit by some geophysicists, then the minimum energy of protons arriving at the equator is a few Mev whereas at the earth's magnetic equator the minimum energy is on the order of 10 Gev.

In order to determine the scope of the hazard due to cosmic ray protons, a computational method was used which was developed by the writer [1]. This work was coded for a computer at Marshall Space Flight Center. The code calculates the proton dose rates behind a multi-layer slab shield which may consist of five distinct layers of different materials. This code also calculates the depth dose in tissue as well as the skin dose. Differential energy spectra and secondary

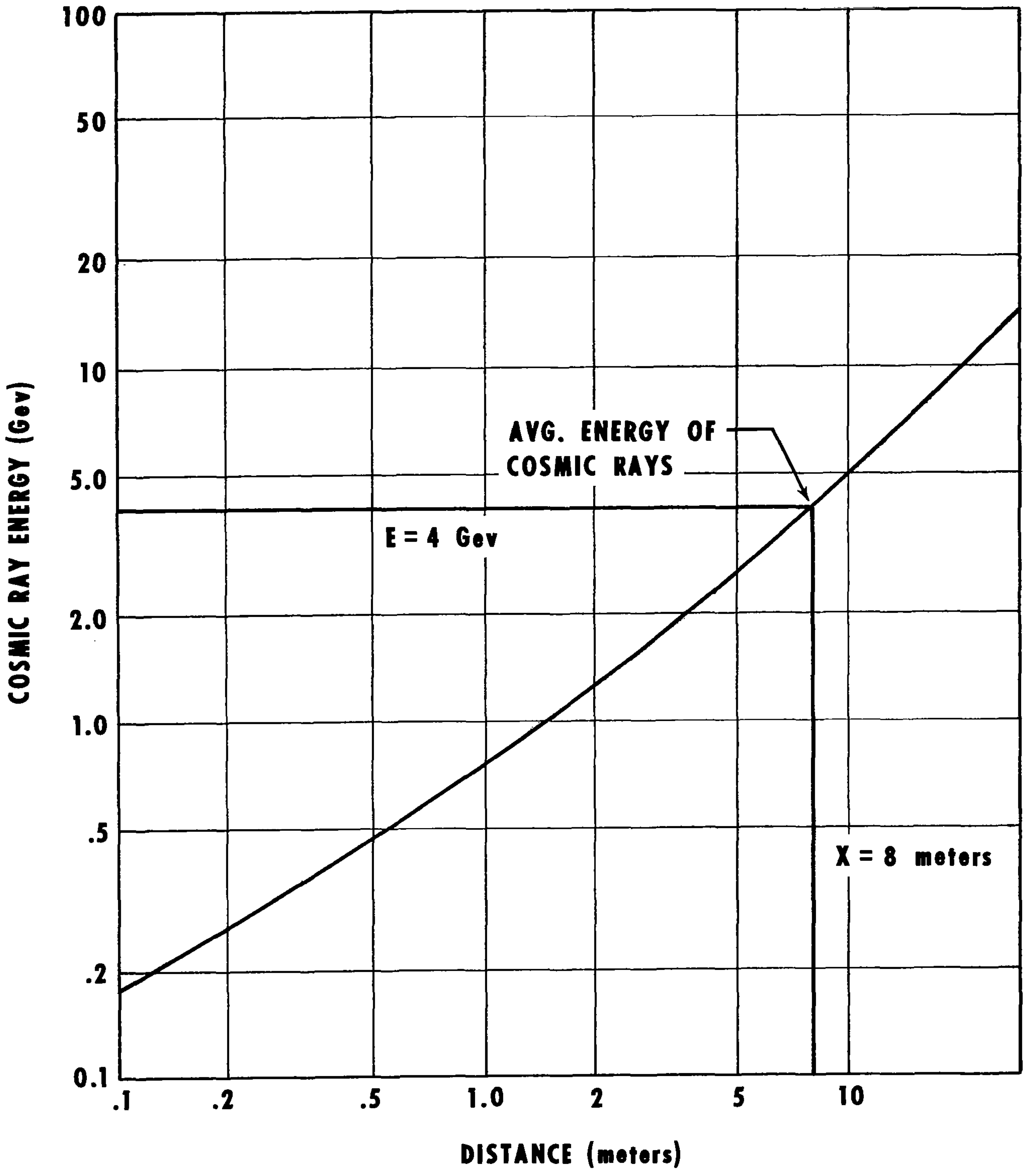

FIGURE 1. DISTANCE OF PENETRATION OF COSMIC RAY PROTONS IN SiO_2

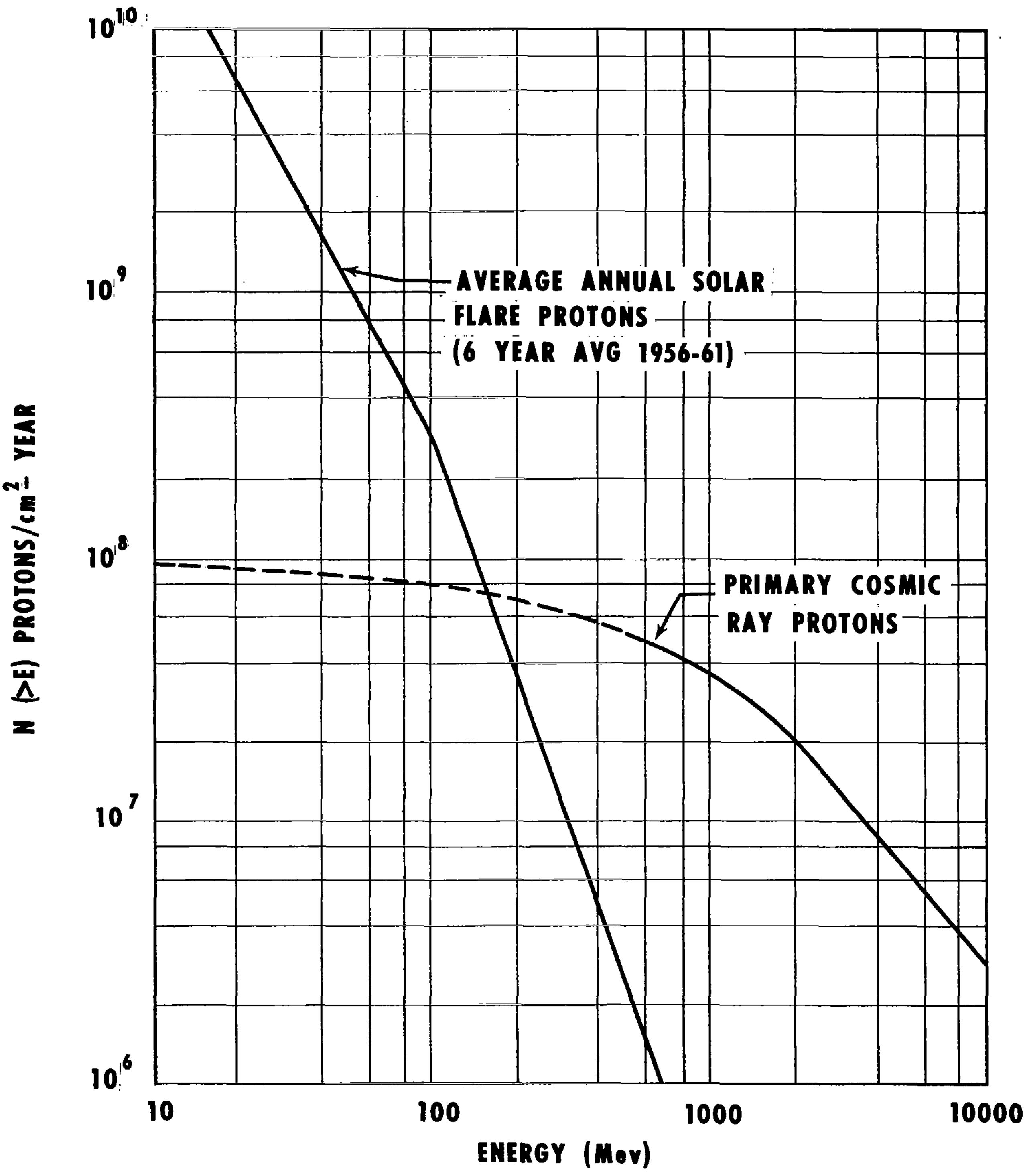

FIGURE 2. INTEGRAL SPECTRA OF SOLAR FLARE AND PRIMARY COSMIC RAYS TIME INTEGRATED OVER ONE YEAR

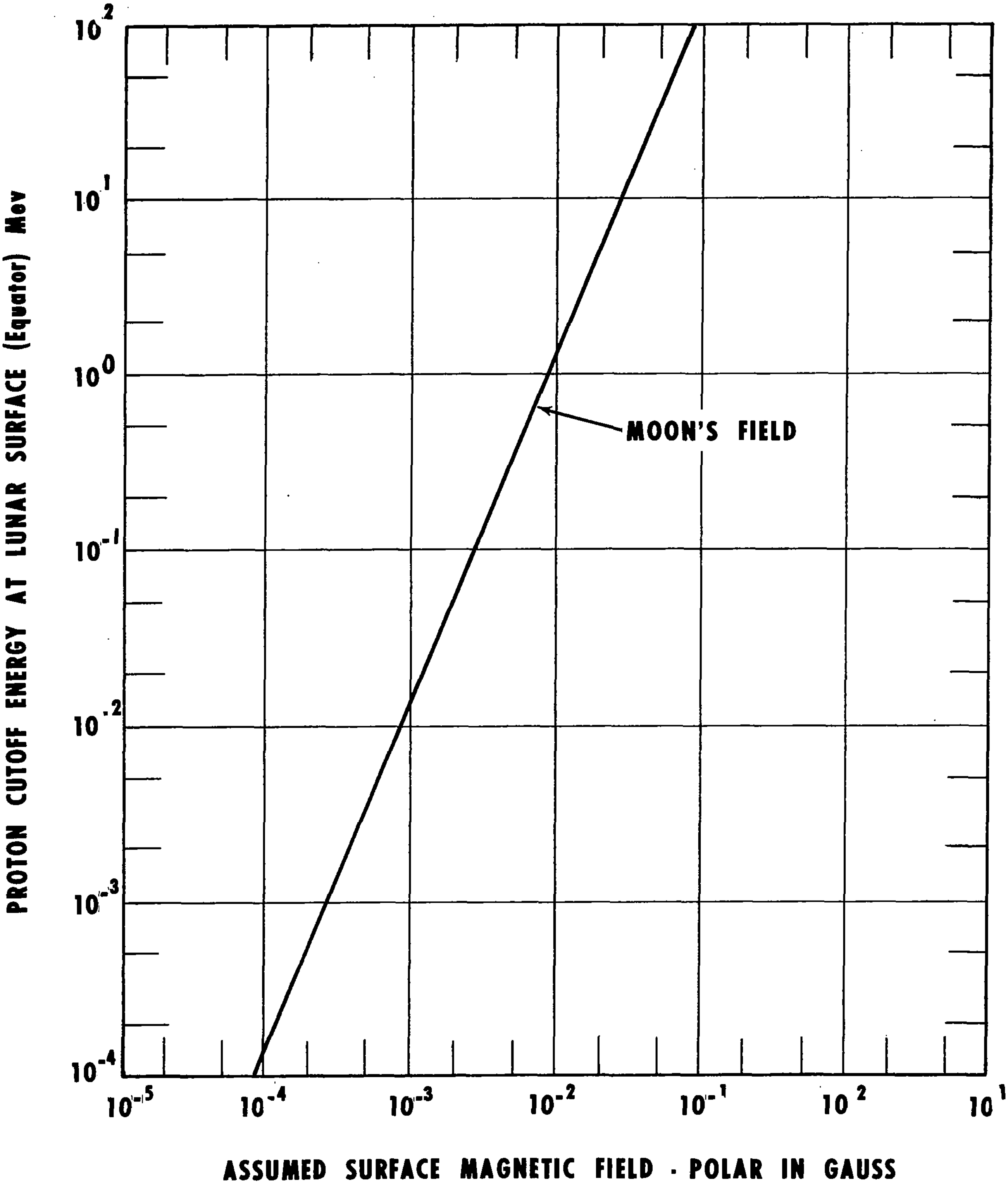

FIGURE 3. PROTON CUTOFF ENERGY AT THE LUNAR SURFACE

particle source terms as a function of depth in the shield can also be found. The incident protons may be either monodirectional or isotropically incident on the shield. The figures to follow which show dose rates as a function of depth for both cosmic rays and solar protons were obtained by the use of this code.

In Figure 4 is shown the dose rate in rads/year from cosmic ray protons as a function of depth in cm of aluminum. The top curve may be used for a hypothetical space craft and the lower curve for the dose of an isotropic flux incident on a surface of great extent such as the lunar surface. This calculation does not include secondary neutrons and protons. The inclusion of the secondaries would have given a more pronounced increase in dose rate around 20 cm. The energy spectrum used for this calculation is shown in Figure 2; however, the incident energy spectrum was truncated below 250 Mev. If the incident energy spectrum was truncated at 100 Mev the dose rates shown would be approximately a factor of two higher for depths less than 21 cm of aluminum but the same for depths greater than 21 cm of aluminum. The justification for the above choice is that it is quite difficult to distinguish between galactic cosmic rays and solar protons at such a low flux (2 particles/cm^2 - sec) when the energies are below 250 Mev.

SOLAR FLARE PROTONS

Solar flare protons are the least understood of all space radiation and the most hazardous to manned space flight. A flare is a sudden brief brightening of a small portion of the solar disk occurring in the vicinity of active sunspot groups. Flares are classified primarily according to their visible size into three groups of importance: 1, 2, or 3 with a plus or minus used to denote flares which are stronger or weaker than the average of their class. The energy spectra and intensities of the proton beams emitted along with the flares vary considerably from flare to flare. Most of the knowledge concerning solar flares has been obtained from terrestrial observation. Several phenomena observable on the earth are associated with solar flares. At the outset of the flare, visible light, ultraviolet light, X-rays, and radio emissions are observed simultaneously, usually lasting about 4 hours. The solar flare protons arrive at the earth within an hour or two after the flare onset. However, this paper is concerned with the radiation environment of the moon and since many of the conditions such as the earth's magnetic field and atmosphere result in phenomena peculiar to the earth, care must be exercised in extrapolating to conditions on the lunar surface. In any case, attempts have been made to arrive at the so-called free space solar proton radiation environment using terrestrial measurements. These are made near the polar regions in conjunction with high altitude balloons and rocket probes. However, at

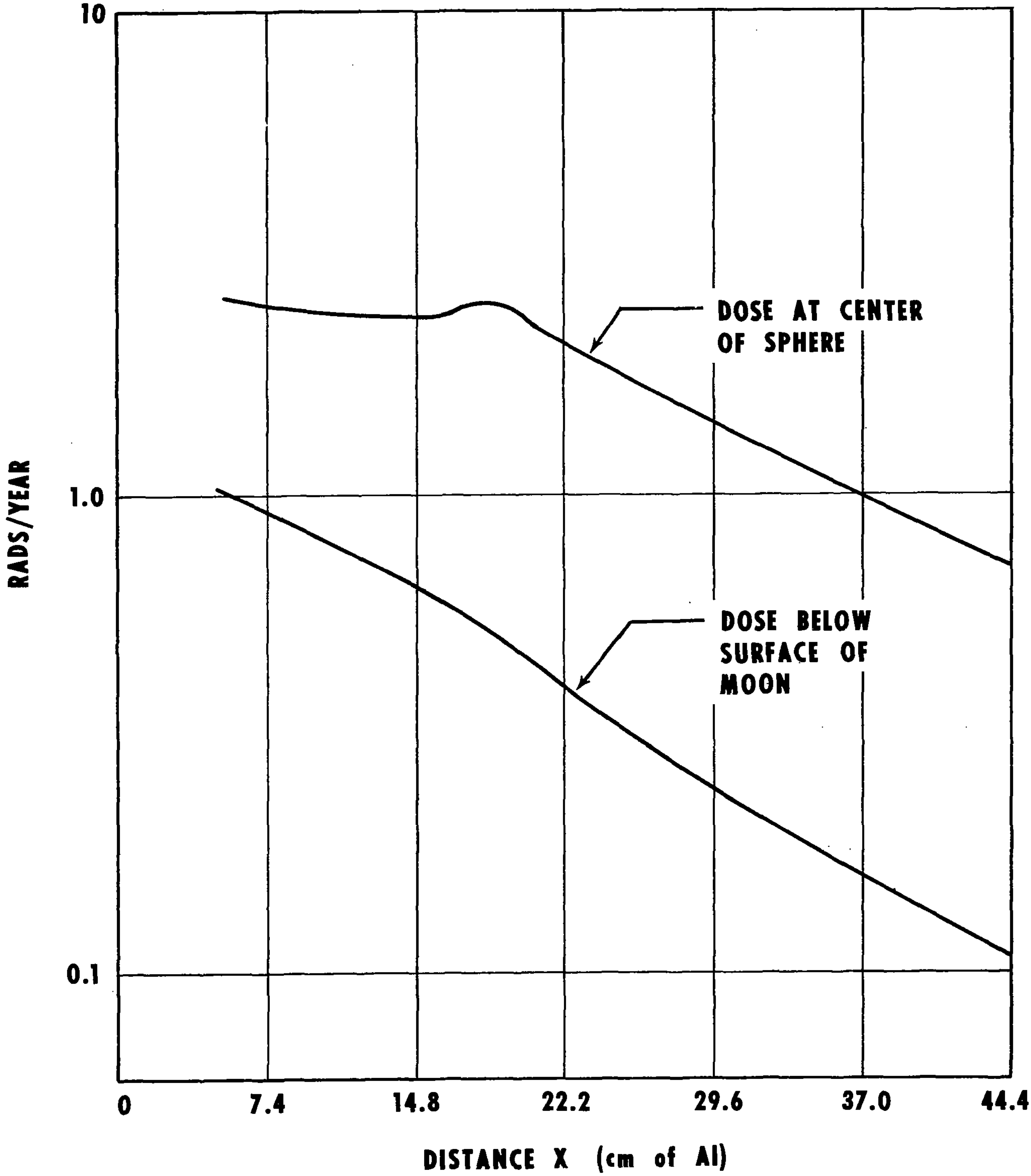

FIGURE 4. COSMIC RAY DOSES AS A FUNCTION OF DEPTH IN ALUMINUM

the lunar surface the magnetic field is sufficiently small that essentially the same energy of solar protons will reach all points on the lunar surface. Also, except for the initial period of the solar flare, the solar protons will be arriving at the moon's surface from all directions in such a manner that it is usually assumed the solar flare protons are isotropically distributed in direction. Finally, the lunar atmosphere is so negligible that any shielding resulting therefrom can be completely ignored. In short, the best estimate of the solar flare proton environment of the moon is the same as that for free space except for the solid angle reduction provided by the moon's surface.

In Figure 5 are shown free space time-integrated differential energy spectra for several large flares from 1956 to 1960*. Each curve is based on a few measurements from different methods such as neutron monitors in balloons, emulsions in rocket probes, and riometer readings near the polar regions. The neutron monitor method detects secondary neutrons when a high energy proton causes a cascade in a lead shield around the neutron counter. The emulsion method detects proton tracks directly. The riometer measures the attenuation of extraterrestrial radio noise due to energetic particles ionizing the upper atmosphere. Because of the earth's magnetic field these particles can enter the earth's atmosphere only in the polar regions. This phenomen is called polar cap absorption and is frequently seen in the literature as "PCA" events. Because of the inaccuracies in extrapolating to the free space environment (no magnetic field or atmosphere), these methods leave much to be desired in terms of accurate shielding calculations. The heavy line curve shown in Figure 5 is based on the average of 30 flares taken from 1956 to 1961. This average curve is used in the proton dose rate calculations shown in Figures 7, 8, and 9.

Table II shows the solar proton primary doses from the most severe 3+ flares occurring since 1956. The data in this table were taken from the "Solar Proton Manual" prepared at Goddard Space Flight Center [2]. It should be noted that the total dose in this table is highly sensitive to the cutoff energy. The first column shows the date of the flare; the second column, the total skin dose for energies above 30 Mev; and the third column, for energies above 100 Mev. Also of particular interest is the occurrence of multiple large flares as in July of 1959 and November of 1960. Such an occurrence on a lunar voyage could be disastrous unless adequate shielding is provided. However, the large dose reductions provided by considering only energies above 100 Mev [equivalent to about 3.7 cm of aluminum shield] should be noted. Thus it seems that primary protons are readily

* The magnitude of many of these flares has been reduced in the past year from a more thorough analysis of the data. See Reference 2.

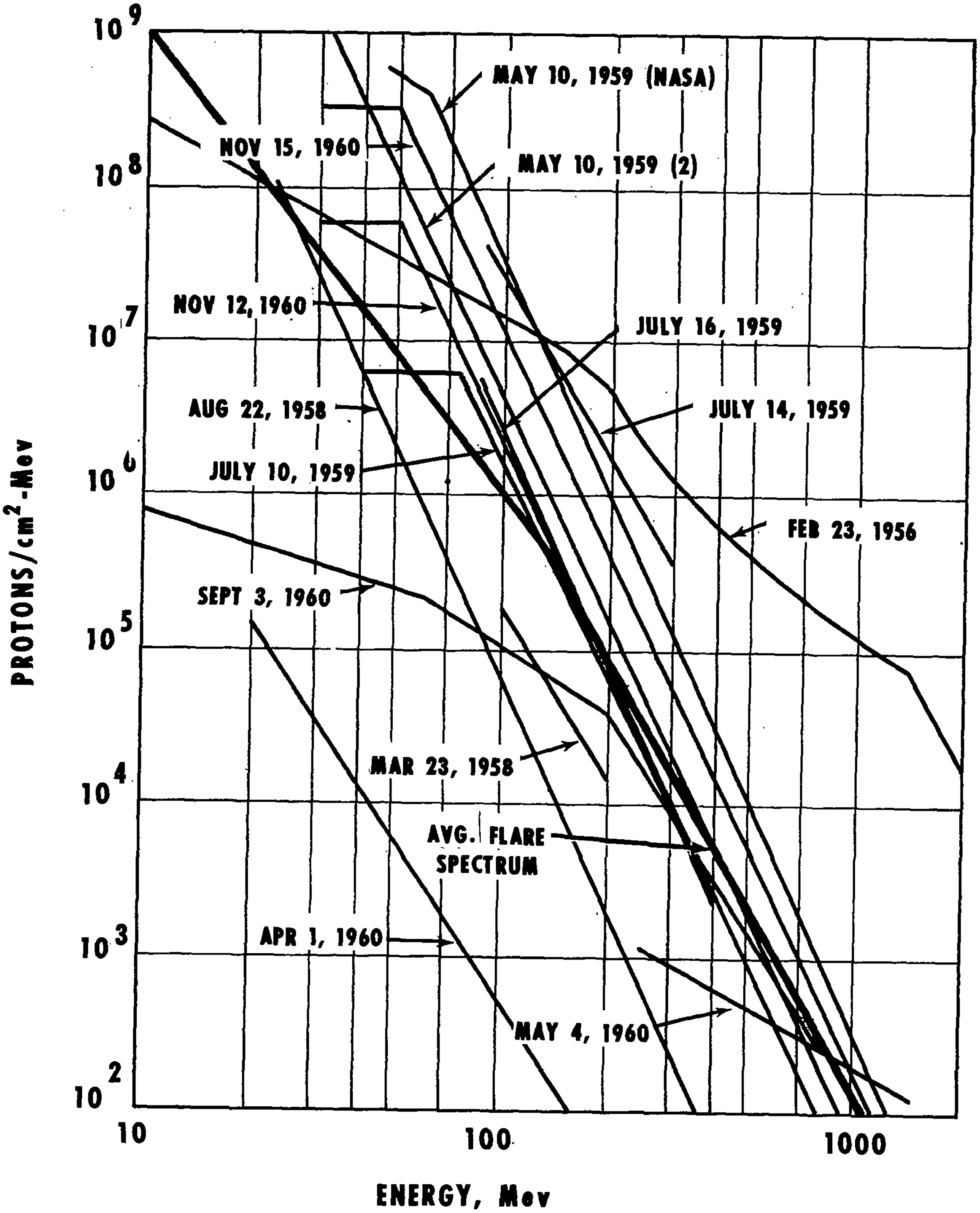

FIGURE 5. TIME INTEGRATED DIFFERENTIAL ENERGY SPECTRA FOR SEVERAL SOLAR PROTON EVENTS COMPARED TO AN AVERAGE FLARE (30 FLARE AVG. FROM 1956 TO 1961)

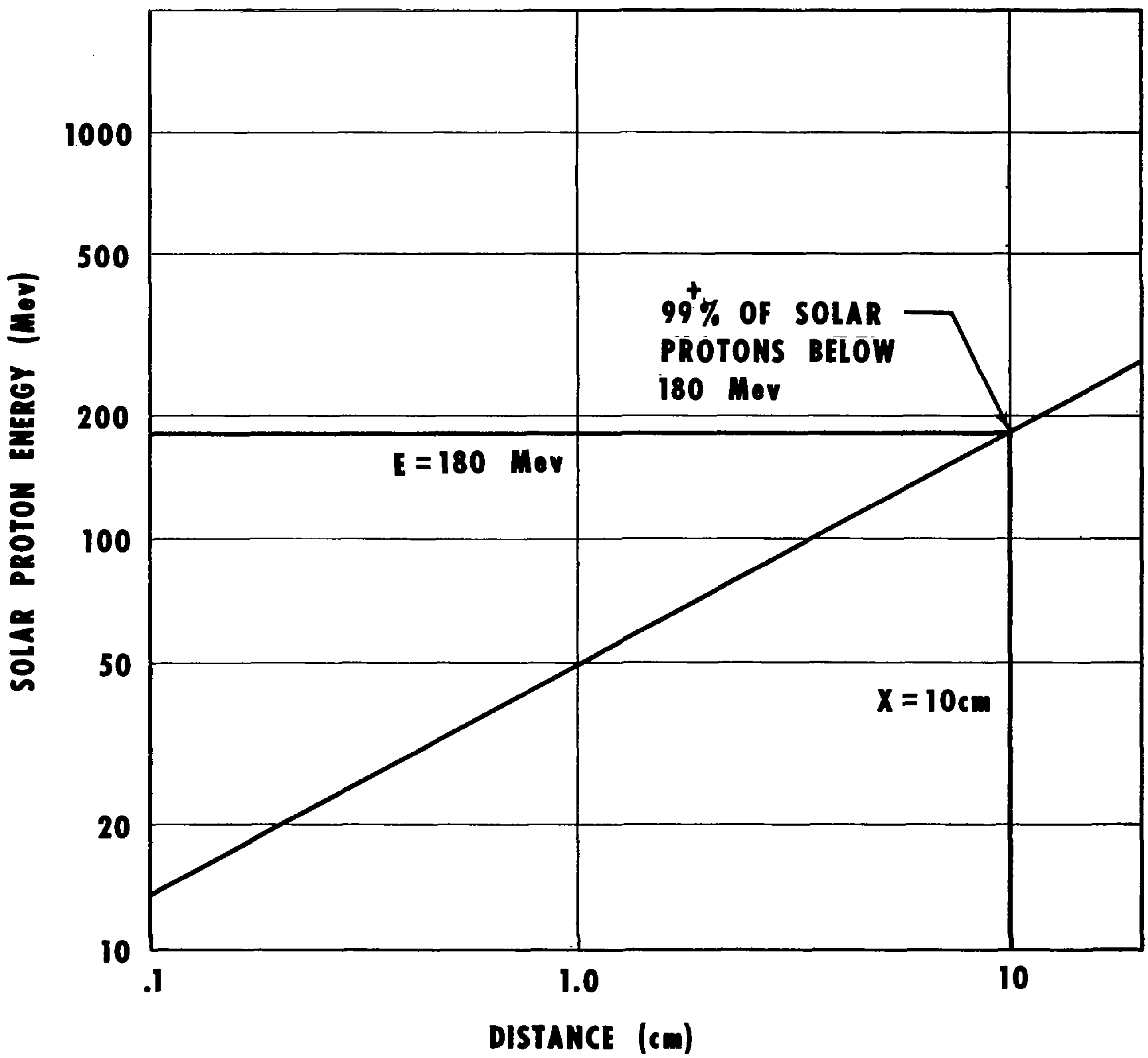

FIGURE 6. DISTANCE OF PENETRATION OF SOLAR PROTONS IN SiO_2

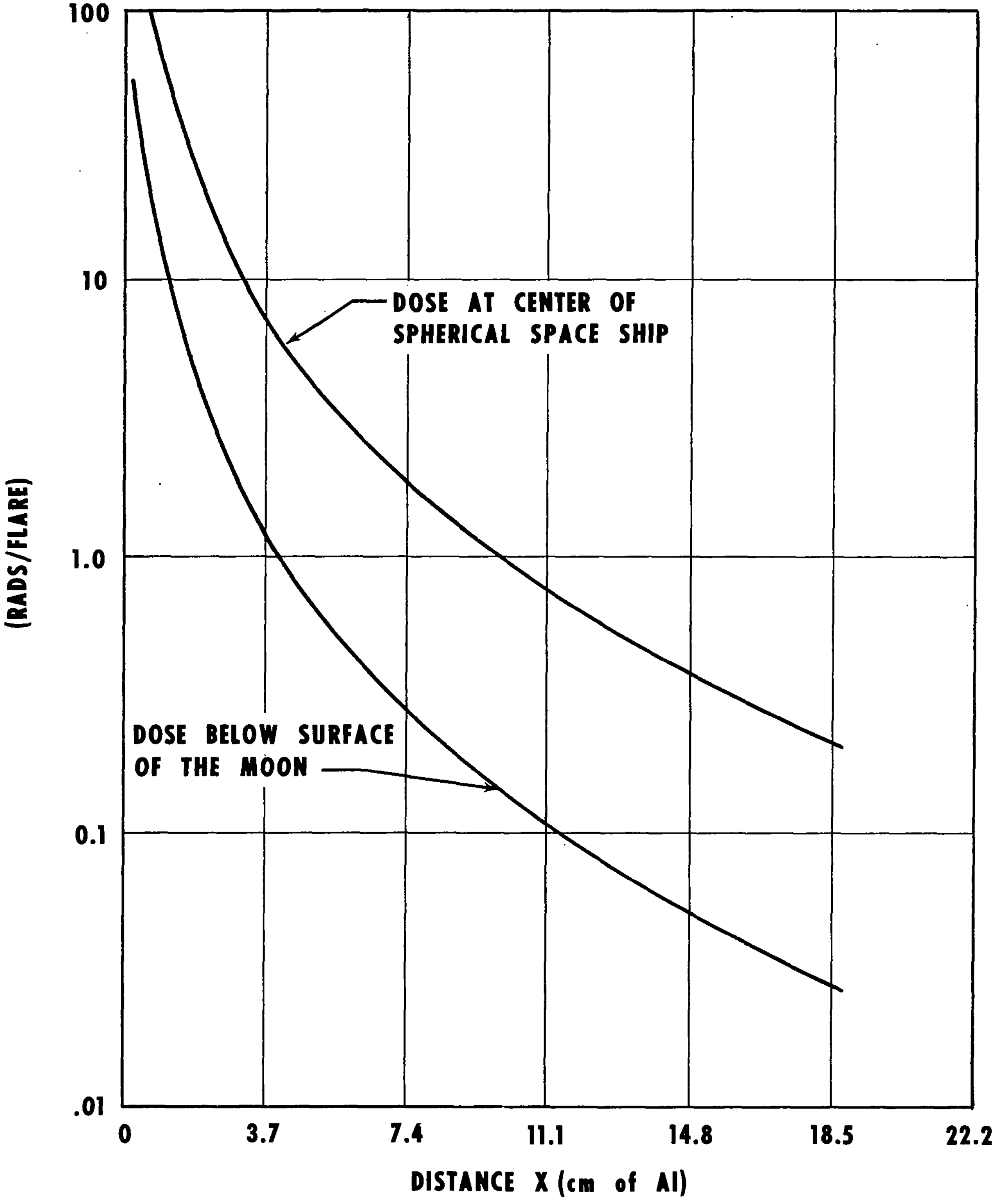

FIGURE 7. RADIATION DOSES FROM AN AVERAGE SOLAR FLARE

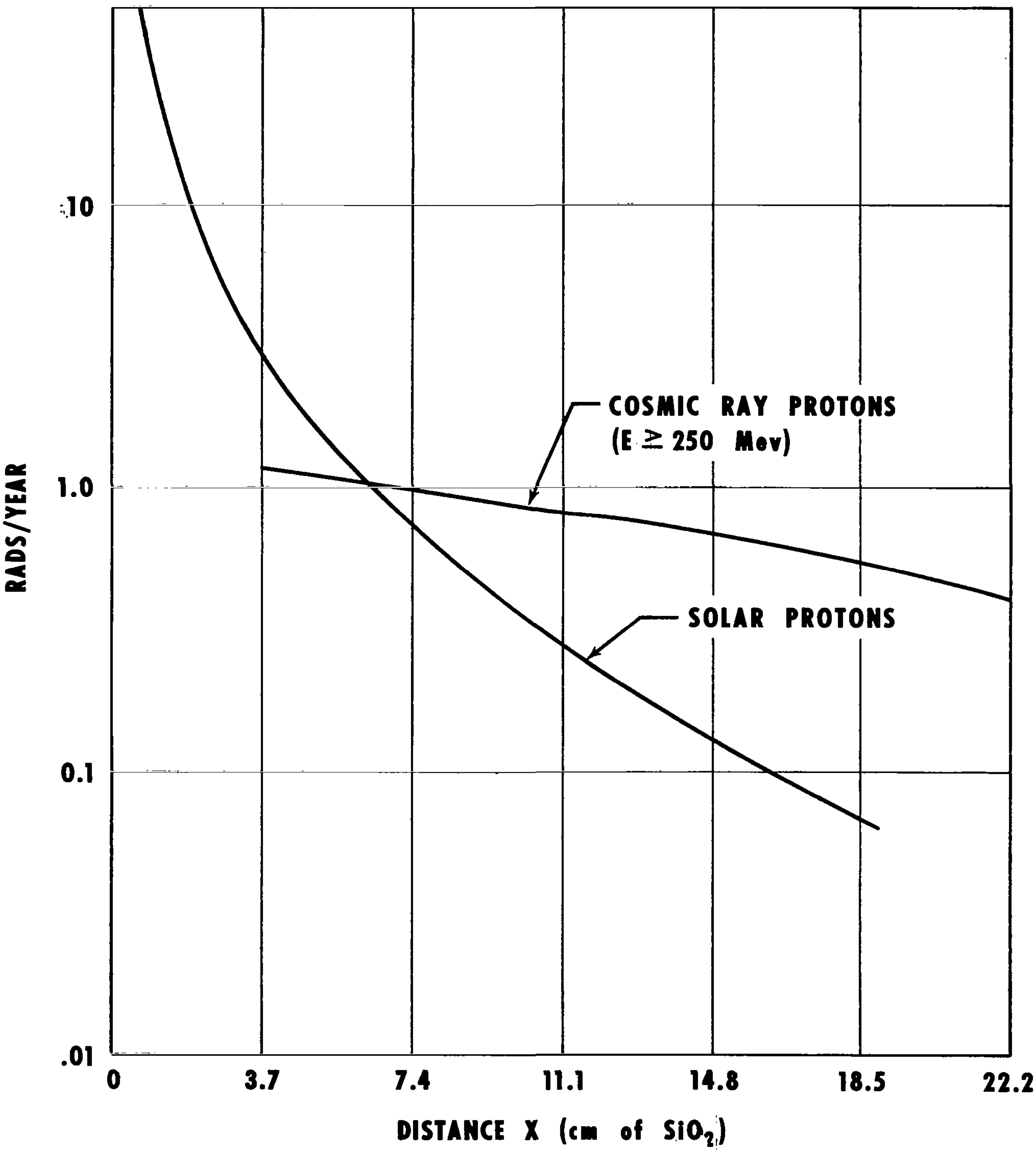

FIGURE 8. RADIATION DOSE UNDER SURFACE OF MOON FROM SOLAR PROTONS AND COSMIC RAYS

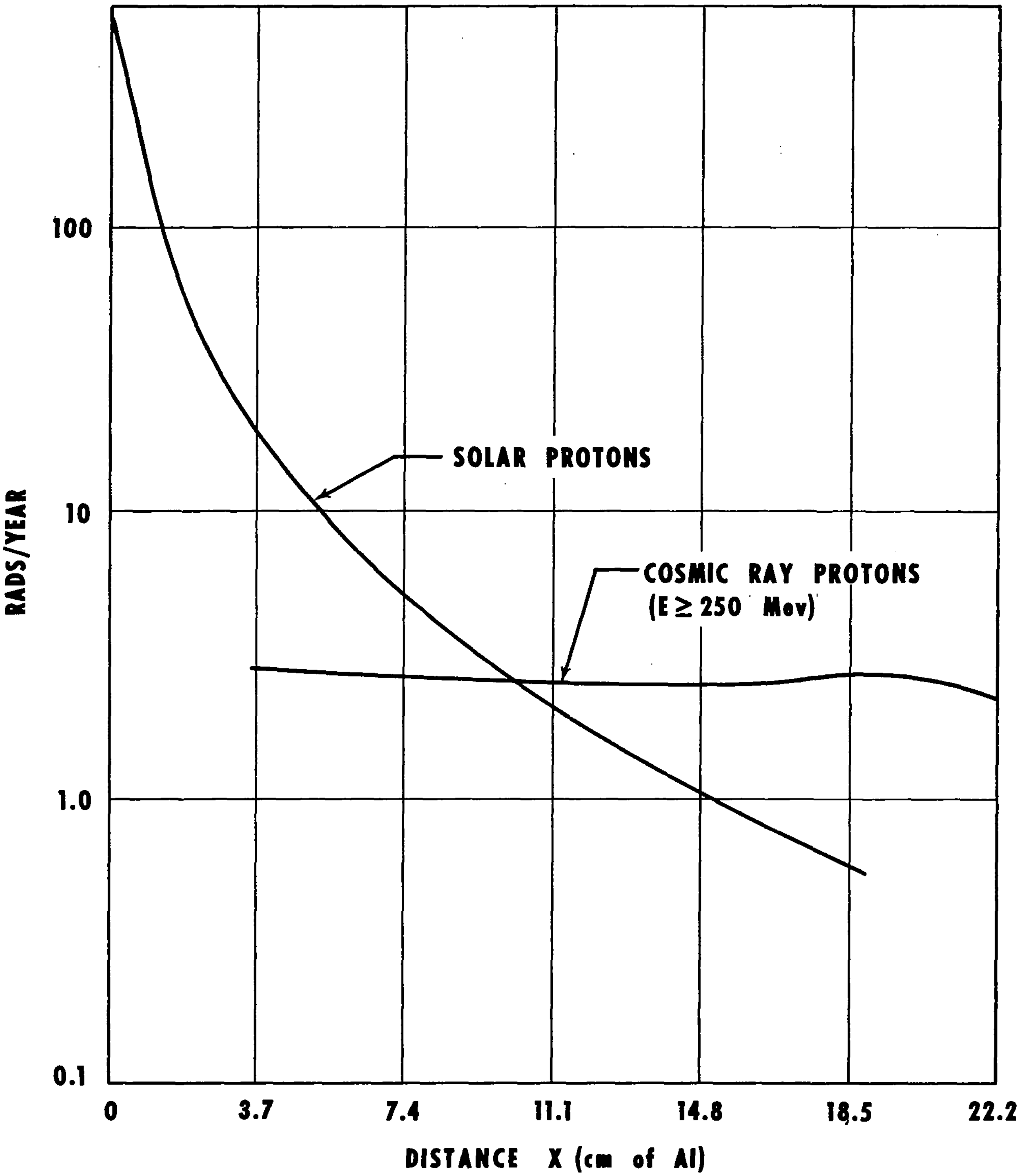

FIGURE 9. RADIATION DOSE AT CENTER OF SPHERE FOR SOLAR PROTONS AND COSMIC RAYS

TABLE II LARGE FREE SPACE RADIATION DOSES FROM SOLAR FLARES OCCURRING DURING THE PAST SEVEN YEARS

DATE	TOTAL SKIN DOSE (RADS) E>30 Mev	TOTAL SKIN DOSE (RADS) E>100 Mev
FEB. 23, 1956	120	28
JAN. 20, 1957	60	1.2
MAR. 23, 1958	50	0.7
JULY 7, 1958	80	1.0
MAY 10, 1959	440	10
JULY 10, 1959	148	11
JULY 14, 1959	177	7.4
JULY 16, 1959	125	19
NOV. 12, 1960	205	33
NOV. 15, 1960	100	12
JULY 18, 1961	27	3

shielded by bulk material. As a final warning, the magnitude of these figures should not be considered as ultimate truth. Other writers have obtained a larger dose for these particular flares in free space. However, these dose rates are probably not too low for the lunar surface since the moon provides about a factor of 2 reduction in incident flux because of total shielding from half of space.

In Figure 6 is shown the thickness of sand (SiO_2) with a density of 2.65 gm/cm^3 required to stop a proton of energy E in Mev. On this graph, which is similar to a previous one for cosmic ray protons, it should be noted that 10 cm of sand will stop over 99 per cent of most solar flare protons. Some care should be exercised in too optimistic an outlook, however, since a fraction of 10 to 30 per cent of all the incident protons, depending on the shield material and thickness, will be converted into secondary neutrons which are not so readily stopped. In fact, when the shield gets to be greater than about 20 cm thick, the secondary neutrons may make a greater contribution to the dose than the primary protons.

In Figure 7 the total dose (rads/flare) is given as a function of depth in aluminum due to primary protons from an average or typical flare both below the lunar surface and at the center of a spherical space ship.

In Figure 8, a comparison of the annual solar flare proton dose rate (rads/year) and the cosmic ray dose rates below the surface of the moon is given. It should be noted that for a depth greater than about 6 cm the cosmic ray protons give a greater average annual dose rate than the solar protons.

In Figure 9 a comparison similar to the previous figure is made, but the dose is given at the center of an aluminum sphere. In this case the annual cosmic ray proton dose exceeds the annual solar proton dose for an aluminum thickness greater than 10 cm. The solar proton spectrum for this curve, as in the previous figure, is based on a six-year average from 1956 to 1961, which included the most active period of the solar cycle. Because the results from the so called average flare may be somewhat misleading, the writer has also chosen a model from a NASA publication [3]. This model is for a two-week mission to the moon. The energy spectra of the protons is based on the assumption that the probability is 0.01 that a greater total proton flux will occur. That is, 99 per cent of all two-week periods between 1956 and 1962 had a smaller total proton flux. The skin dose (rads) from this flare as a function of shield thickness at the center of an aluminum sphere is shown in Figure 10. In order to translate such a curve into a meaningful hazard on the lunar surface inside of different structures, Figures 11, 12, and 13 are presented. A discussion of the methods used in this work are given in Reference 4.

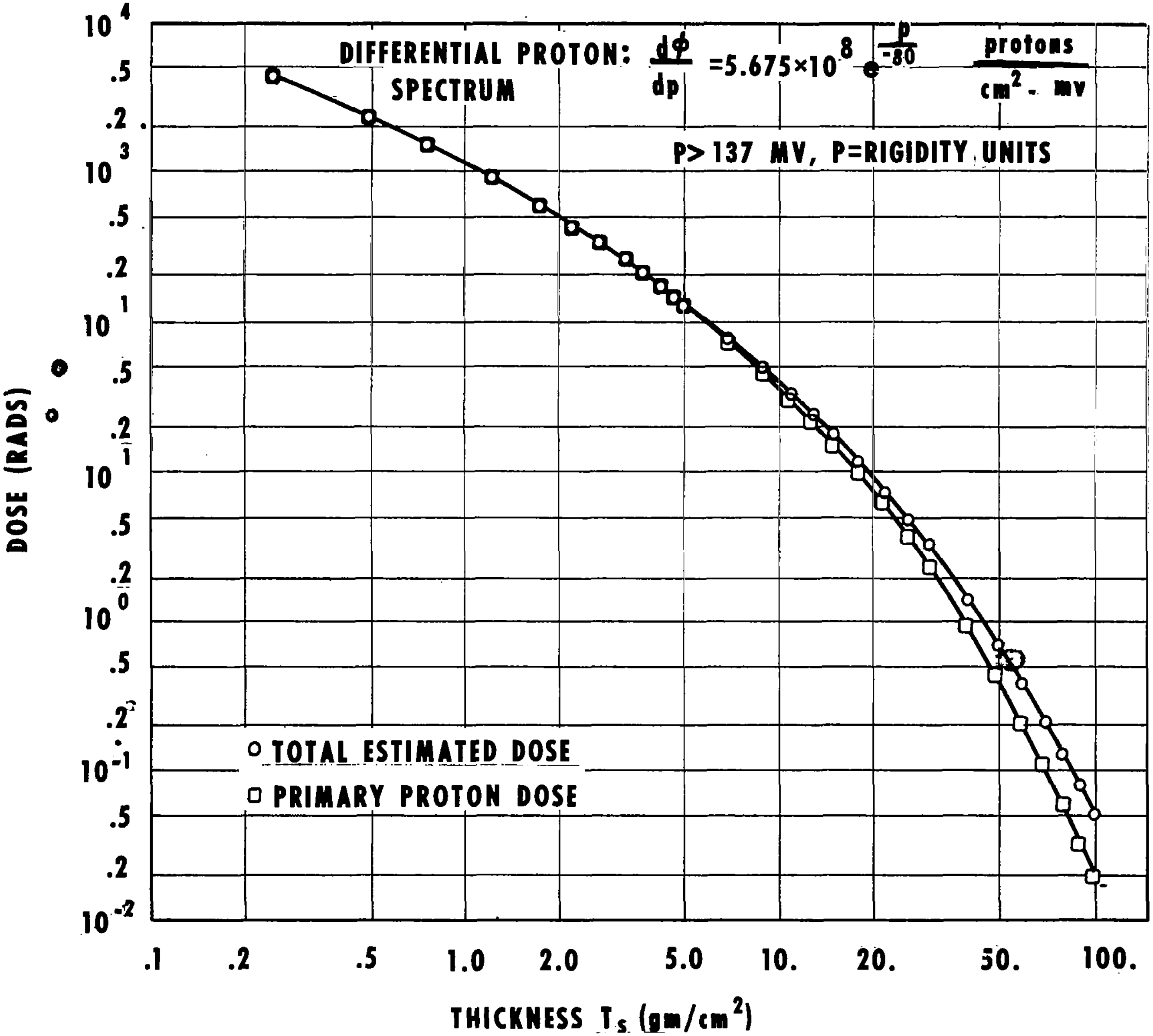

FIGURE 10. FLARE PROTON DOSE AS A FUNCTION OF THICKNESS OF ALUMINUM

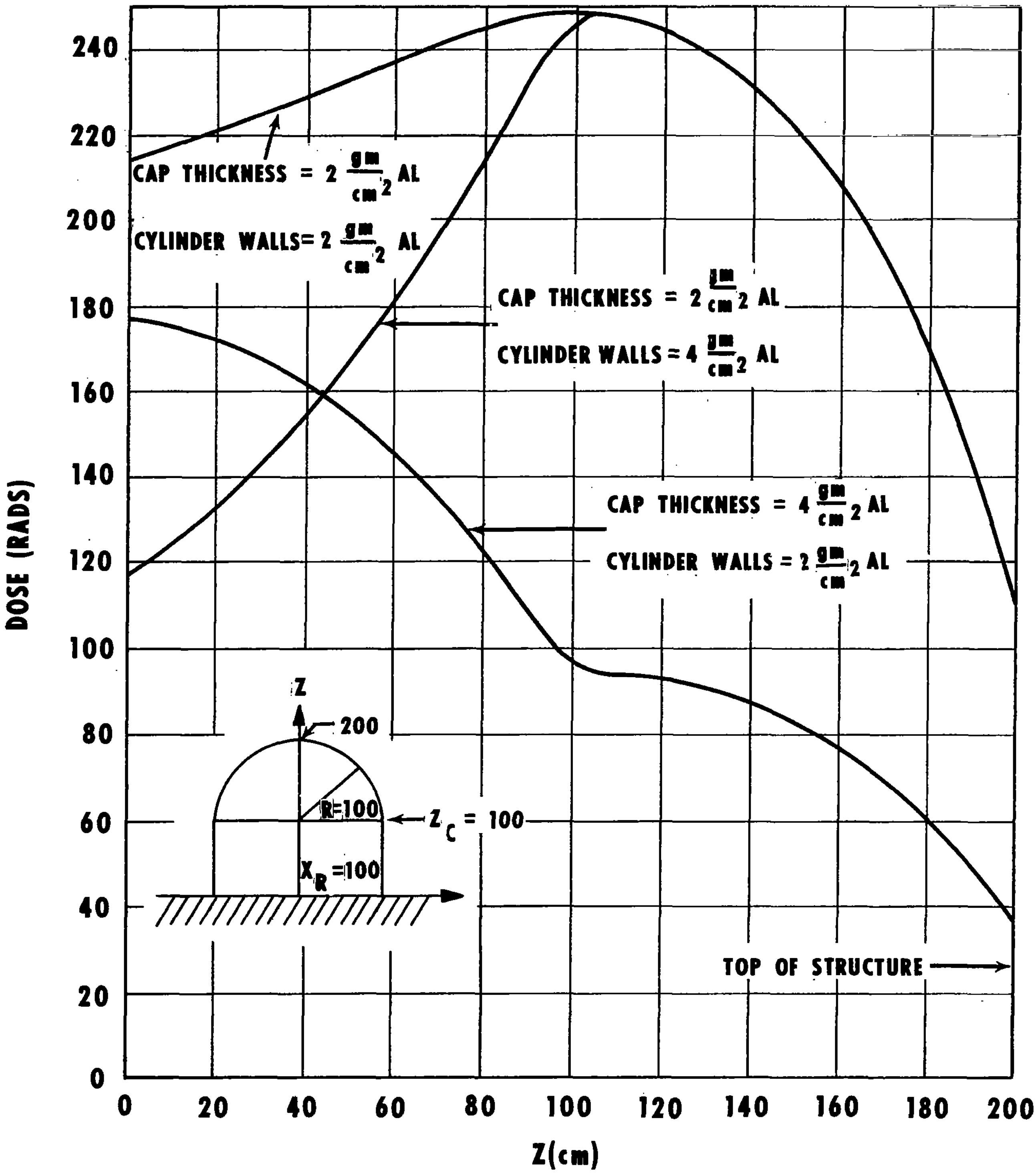

FIGURE 11. CENTER LINE DOSE VERSUS DISTANCE FROM BASE OF CYLINDER WITH SPHERICAL CAP

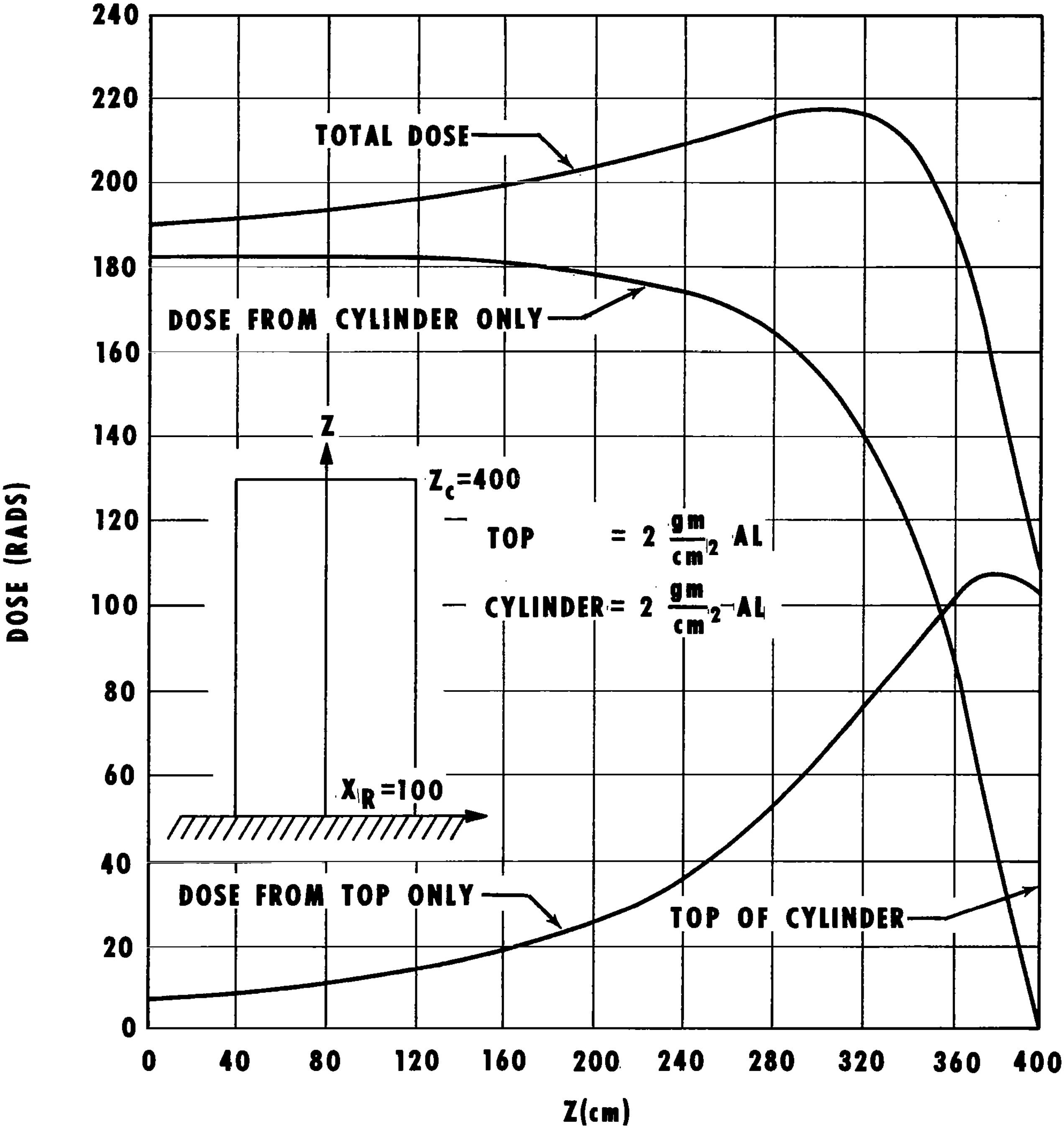

FIGURE 12. CENTER LINE DOSE VERSUS DISTANCE FROM BASE OF FLAT TOP CYLINDER

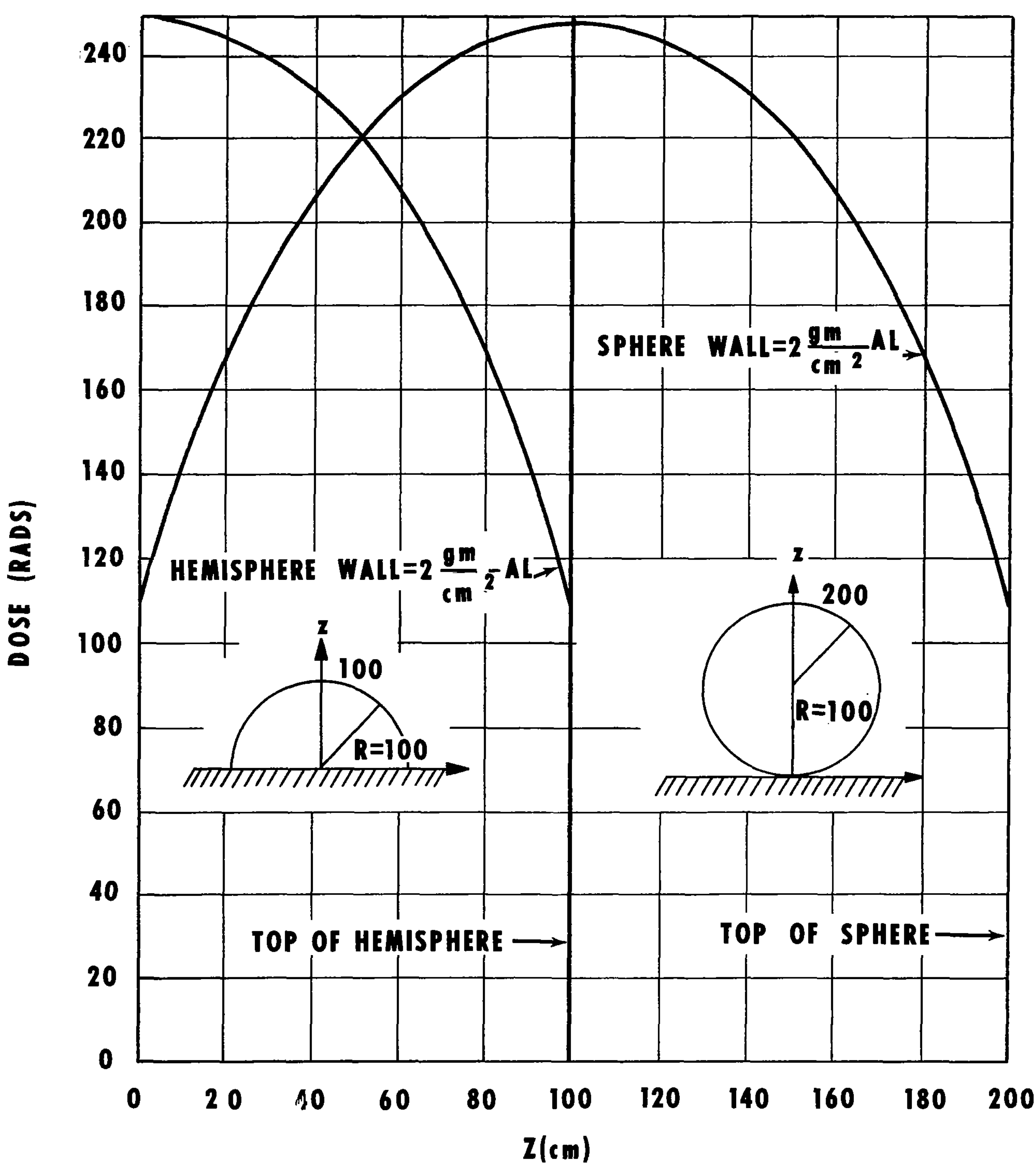

FIGURE 13. Z AXIS DOSE VERSUS DISTANCE FROM GROUND OF HEMISPHERE AND SPHERE

Because of the importance of solar flares to manned space flight, it seems justifiable to discuss the methods and status of flare predictions even though this is primarily a part of solar physics.

The sun is a variable star with a small range in brightness. Its optical variations are easily observed with various types of equipment. Observations of the sun go back in history to a study of the sunspots by the ancient Chinese. In modern times, the past two hundred years, the sunspot cycle is known to have varied from nine to thirteen years, with a mean value of about eleven years. But it has not yet been possible to predict the maximum of this cycle in advance - let alone to predict day-to-day solar activity with any degree of reliability. Certain solar physicists maintain that the sunspot number is still the most easily observed indicator of solar activity, but a solar flare event still defies successful prediction except in the most general terms and the sunspot number alone cannot be used to predict accurately dangerous periods for space flight or lunar exploration. Another phenomenon used for prediction is the magnetic cycle of the sunspots. This cycle refers to the reversal of polarity of the leader and follower of a pair of large spots. Other indicators which are used are outlined below.

A few ideas seem fairly well established; for example, a high degree of solar activity is a necessary condition for a solar cosmic ray storm and these solar storms are usually accompanied by solar flares of intensity 3+. The flare indicators used in making predictions at the Sacramento Peak Observatory are the following:

1. Presence of a large complicated sunspot group.

2. Presence of a complicated magnetic field with many poles of opposite sign.

3. Presence of very bright plages in the light of hydrogen or ionized calcium lines.

4. Occurrence of frequent outbursts of radio emission with a high background level.

5. Presence of hot spots in the overlying corona.

6. Presence of high level of minor activity with numerous small flares, loop prominences, and surges.

It should be emphasized that the presence of these indicators is a warning of a major flare activity within a few days. But even if all are present, no major flare activity may result.

Some additional possible flare indicators are now under study, and it is anticipated that they may throw light on the problem and increase the reliability of the predictions. Some solar physicists believe that the expansion of the work on solar magnetic models will give some real hope for flare prediction, but all that can be said at the present time is that more work in all aspects of solar physics must be done before sufficiently reliable predictions of solar flares can be made.

Many attempts at statistical studies have been made, but one cannot place much reliance on these statistical studies because the sample of data is rather small. It should also be pointed out that every flare differs from every other so that no exact relationship exists between observable features. A proper statistical study must involve a large number of events in order to make more specific statements about flare occurrence, duration, and intensity.

Because of the complexity of solar phenomena and their measurements, it is not appropriate in this discussion on the radiation environment of the moon to pursue further the problem of solar flare predictions. Hence we will proceed to the next topic.

INDUCED SURFACE RADIATION

The moon's surface is activated as a result of bombardment by energetic particles. Such activation can result from the processes of spallation, fission, fragmentation, and capture. The indirect radioactivity is a result of the deexcitation and decay of the resulting nuclei together with evaporation of neutrons and protons. Proper treatment of the lunar surface activation is not possible because of a lack of knowledge of the surface composition, energy spectra of the incident particles, and reaction cross sections. Among the areas of uncertainty is the elemental composition of the lunar crust. Table III shows the elemental composition of three assumed lunar crust models. The first is an "earth crust," the second is a basalt or volcanic active crust, and the third is a "meteoric crust." The major difference occurs in the meteoric model which shows 30 per cent iron and 12 per cent magnesium replacing aluminum in the other two crust models.

John A. Barton of Boeing has made calculations of the surface activity assuming the "meteoric" model for the lunar surface [4]. The justification for his assumption is that a reasonable estimate of meteoric accumulation is seventy-five tons per day on the total lunar surface. This corresponds to a total buildup of about 64 cm average depth, if the accumulation has been for 4×10^9 years with an average density of 2 gm/cm^3. The results of Barton's calculations are listed in Table IV along with calculations of the writer.

TABLE III LUNAR CRUST MODELS (AVERAGE)

	MODEL		
ELEMENT	EARTH CRUST	BASALT	METEORIC
O	46.60%	46.12%	32.76%
Si	27.72	24.26	16.38
Al	8.13	8.10	----
Fe	5.00	4.97	30.11
Ni	----	----	2.20
Mg	2.09	5.25	12.42
Ca	3.63	5.21	1.53
Cl	----	----	1.35
Na	2.83	2.04	0.59
K	2.59	2.08	----

TABLE IV LUNAR SURFACE RADIATION DOSES - REMS/WEEK

RADIATION SOURCE	STEADY STATE (BARTON)	ACTIVE SUN (BARTON)	STEADY STATE (BURRELL)	ACTIVE SUN (BURRELL)
DIRECT CORPUSCULAR PRIMARY COSMIC AND SOLAR PROTONS	MAX 0.34 MIN 0.12	100 --------	0.10 0.05	60
INDUCED RADIATION (NEUTRONS & GAMMAS)	.0005	0.31	.0007	0.72
LUNAR CRUST RADIOACTIVITY				
GRANITE	.0020	.0020	-------	------
METEORIC MATERIAL	.0002	.0002	-------	------
BASALT	.0005	.0005	-------	------
TOTAL	MAX .34 MIN .12	100	MAX .10 MIN .05	~61

The calculations of the writer for induced surface radiation are of a very simple nature. In these calculations, an average material between iron and oxygen was postulated. A reaction cross section of .01 cm^2/gm was assumed. Most of the solar flare protons are stopped within 30 gm/cm^2 so that approximately 25 per cent of all incident solar protons result in reactions that could yield high energy cascade particles and residual evaporation of the excited nucleus. It was then postulated that for each favorable collision there are 0.8 cascade neutrons with a typical energy of 40 Mev and 0.6 evaporation neutrons with an average energy of 2 Mev. For cosmic rays it was assumed that all protons had one collision favorable for secondaries since their penetration is so great. However, the evaporation neutrons occur so deeply below the surface that few low energy particles can escape. Thus only cascade particles from cosmic rays were considered. Also cascade particles tend to go in the direction of the incident protons, resulting in a strongly forward direction for secondaries. Therefore, an estimate was made that only about one-twentieth of all cascade neutrons would exit the lunar surface, whereas for the solar proton-induced evaporation neutrons, it was assumed that one-fourth would exit the surface. With a cosmic ray flux of 1 proton/cm^2-sec incident on the moon and a solar proton flux of 1×10^9 protons/week, the results shown in Table IV were obtained. The agreement shown between Barton and Burrell seems reasonable considering the difference in methods and assumptions used. It should be pointed out that the writer's calculations did not include secondary gammas, and the calculations opposite "direct corpuscular" and under "active sun" include an aluminum shield of 0.37 cm (1/8 in). If extrapolations are made to near 0 cm, a dose of well over 100 rem/flare would be obtained.

NATURAL SURFACE RADIOACTIVITY

The last topic to be discussed is the natural surface radioactivity of the moon. Part of the radioactivity at the surface of the moon will be caused by trace quantities of naturally occurring radioactive elements. If a distribution of elements of the moon is assumed to be the same as that of the earth, almost all of the radioactivity will be from uranium 238, uranium 235, thorium, potassium 40, and their decay chain products. Under these conditions the weekly radiation dose would be the same as on the earth or from 0.3 to 2 mr/week. It is more probable that the lunar surface has a composition similar to basalt. Also the radioactive materials in meteorite deposits have to be considered if the moon is covered with 64 cm as conjectured in a previous section. The results of all three assumptions are shown in the last row of Table IV. The results shown in Table IV indicate that the earth crust model depicted by granite would give a greater dose than either a basalt or meteoric lunar crust. Also it is worth noting that the steady state condition of induced radiation is about the same order of magnitude as the naturally occurring radioactivity.

CONCLUSIONS

In summary, the foregoing discussion of the lunar radiation environment has not been exhaustive in any sense of the word. There are many important factors that have not been adequately treated, the foremost of these being the production of secondary particles from high energy protons. Much research is going on in this area at the present and by the time the first astronaut lands on the moon, a much better estimate of the radiation environment will be available. However, after examining the various aspects of the lunar radiation environment, it seems a fair conclusion that the radiation hazard will not be a critical factor in early exploration of the moon. It seems the only serious hazard is that of solar flares and the fact that bulk shielding is effective and available on the lunar surface will reduce solar flares to a phenomenon similar to hurricanes on the earth, that is, a few inches of extra shielding for a few days should reduce the radiation hazard to acceptable proportions.

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Chapter 5

THE LUNAR THERMAL ENVIRONMENT

THE THERMAL MODEL OF THE MOON

By

Gerhard B. Heller *

INTRODUCTION

The surface characteristics of the moon are being studied intensively by many investigators. The field of knowledge is, therefore, subject to rapid changes and new insight. However, many ideas are of a speculative and intuitive nature, because no direct analysis can be made before the first landing on the moon. This paper has to be considered in the time frame of a rapidly evolving field. It constitutes the status and the author's interpretations as of the summer of 1963.

Presently, all of our knowledge is derived from earth-based observations, using various bands of the electromagnetic spectrum for which the earth's atmosphere is transparent. These windows are:

The near UV of the solar spectrum reflected from the moon

The visible light reflected from the moon

The near IR reflected from the moon

The thermal IR of 8 to 13 micrometers emitted from the moon

The thermal mm and cm radiowaves emitted from the moon

The radio signals in cm and m bands from the earth reflected from the moon

This paper will deal only with measurements in these wavelengths and with theoretical studies of the results, and the derivation of a thermal model of the surface of the moon. No assumptions as to the origin or speculations of the composition of the surface of the moon will be used in these discussions. However, it is expected that the results of the analytical studies based upon these measurements can contribute to all fields of lunar physics and can help in an understanding of other phenomena which cannot be determined directly by

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earth-based measurements. Additional knowledge can be expected from results to be obtained from various flight projects, such as Ranger, Surveyor, and the Lunar Orbiter. The studies will be of value in comparing results obtained from these flight projects. However, the thermal model derived from electromagnetic measurements will mainly be of great value for Apollo and Apollo-connected projects like the Apollo Logistic Support System, and the future scientific exploration of the moon. The thermal model will be useful for lunar physics, but will also be of great importance for the thermal design of lunar surface craft and spacecraft in close lunar orbits [1]. This point will become apparent in the discussion of the angular dependence of lunar reflectance and emittance.

Due to the unique radiative characteristics of the moon, analytical methods and computer programs to solve the radiative heat transfer developed for earth or near-earth vehicles are not directly applicable.

The main purpose of this paper is to describe our present knowledge of the moon based upon actual measurements. It is well known that differences in the results and differences in the interpretation of results are common in the literature. These differences will be pointed out; however, emphasis will be on those aspects for which common agreement exists and for which the measurements can be correlated with theory. In some cases only additional, more accurate, or more detailed measurements can resolve the discrepancies. The most fruitful investigations in this field are by researchers working on all three aspects, namely:

Astronomical measurements

Theoretical analysis

Simulated laboratory experiments

CHARACTERISTICS OF THE MOON'S SURFACE

The moon's surface has characteristics which are unique in all aspects - different from any natural surface on the earth. Some characteristics have been simulated in the laboratory by excellent experimental work. However, far-reaching conclusions should not be drawn from a single measurement unless all measurements at all wavelengths can be correlated with these results. To the author's knowledge, no attempt has been made to arrive at a consistent model which takes measurements at the various wavelengths into account, and which can explain the discrepancies between these measurements.

A difficulty which is connected with earth-based measurements is the limitation of the resolution, which is .3 sec of arc or 550 m for the visible; for the best measurements in the IR, the resolution has been 8 sec or 15 km. The measurements, therefore, constitute average values of a large area. This is a serious limitation for the determination of the size of surface features. However, as will be seen, it is not a serious limitation for determination of the radiative characteristics and the thermal model of the moon, because most of these general characteristics are valid over the total surface of the moon, and are completely different from terrestrial surfaces.

A. CHARACTERISTICS IN THE RANGE OF THE SOLAR SPECTRUM

1. Scattering

In the narrow band of visible light which is part of the solar electromagnetic radiation spectrum, the lunar surface shows a strong backscattering in the direction of the incident light ray. Figure 1, based upon B. Hapke [2, 3] and Van Diggelen [4], shows the brightness as a function of the angle of illumination. An angle of 0 degree means light source and observer are lined up with each other, and 90 degrees means that the observer is at right angle to the light source. Figure 1 shows the situation for full moon for the selenographic longitude of 0 degree. Two Lambert surfaces are shown for two lunar latitudes of 0 and 45 degrees. The scattering curve for the lunar surface deviates strongly from an ideal Lambert spherical surface. The intensity drops off sharply with the angle. At 30 degrees, the brightness of an ideal surface (and very nearly so for an earth material) drops to 87 per cent of its peak value; at the moon, it drops off to 50 per cent. The peak value does not decrease with latitude. Figure 2 shows the same relationship as Figure 1 for a selenographic longitude of 60 degrees. In this case, the peak for the lunar backscattering curve does not coincide with the peak of the ideal curve which is always at 0 degree angle of illumination. The most interesting case is given for a selenographic longitude of 90 degrees. The Lambert brightness goes to zero; however, the lunar brightness does not drop off at the limb. Figure 2 also shows a computed curve which is based on a simple model, and measurements by Van Diggelen and Sytinskaya. It should be pointed out that, due to the interference of the earth, the point of 0 degree angle between sun vector and earth observer vector cannot be measured. The closest measuring point is 1-1/2 degrees. Due to the steepness of the light scattering curve, this fact introduces a considerable error into the absolute values of the ratios.

It is significant to note that this electromagnetic property is valid at any place on the lunar surface -- in the mare areas, in the mountains, and in the crater areas. It also applies to the vertical wall. Figure 3 shows the indicatrices

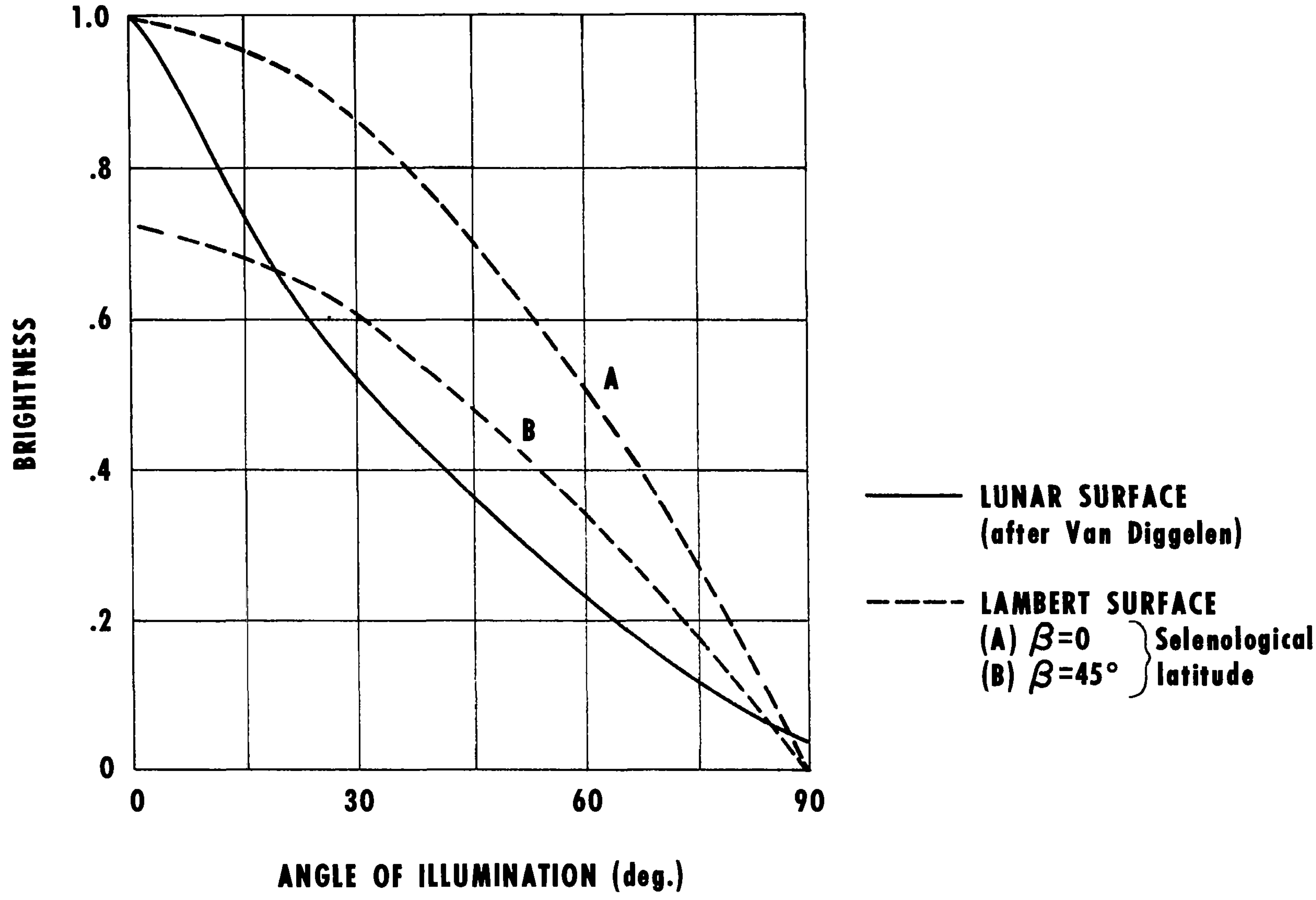

FIGURE 1. BRIGHTNESS OF LUNAR SURFACE AS A FUNCTION OF THE ANGLE OF ILLUMINATION
(Angle of observation $\epsilon = 0°$)

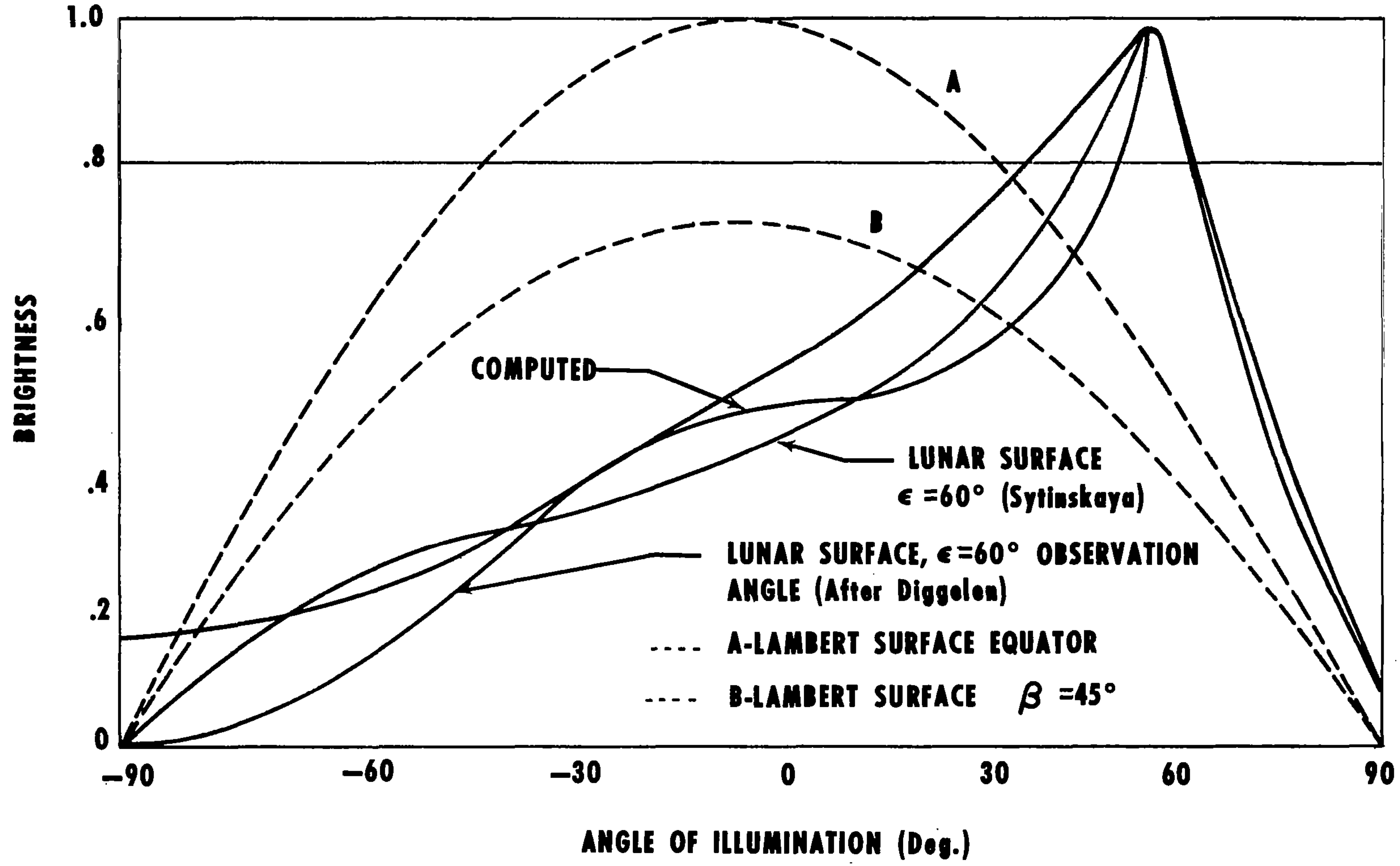

FIGURE 2. LUNATION CURVES FOR REGIONS WITH SELENOGRAPHIC LONGITUDES OF 60°

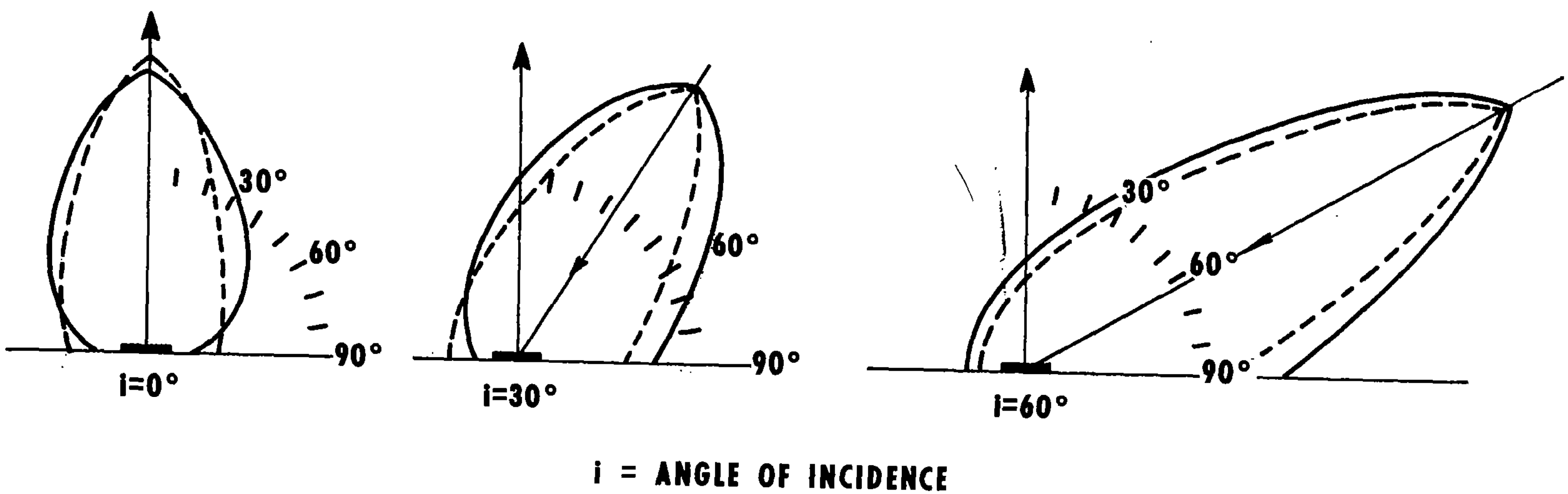

FIGURE 3. INDICATRICES OF REFLECTION: THE FULL LINES REFER TO THE LUNAR MOUNTAINOUS REGIONS: THE DOTTED LINES, TO THE MARIA (AFTER ORLOVA)

of the lunar thermal properties in the visible spectrum for three different angles of incidence taken from Reference 5. There is only a slight difference between mountains and mare. Also, there is very little difference between dark areas and the crater rays. There is no difference in the general characteristics between the oldest lunar areas, 4.5×10^9 years old, and the most recent lunar feature, the crater Tycho, whose age has been estimated by Sinton on the basis of thermal measurements to be a maximum of 10^7 years, [6] and later by Shorthill and Saari to be 5×10^5 years [7]. However, the maximum of the brightness curve is displaced for Tycho and about nine other craters by 10 degrees to a phase angle of 100 degrees. This fact cannot be explained at the present time. If we could find an even more recent lunar crater that has not yet developed this unique surface layer, we would be able to draw conclusions as to the mechanism which leads to its buildup.

The strong angular dependence of visible light from surface features of the moon is expected to affect strongly the ability to visibly distinguish lunar surface formations. It will require large dynamic ranges for photographic and TV cameras.

2. Polarization

Another unique property in the visible region is the polarization of light reflected from the moon [8, 9, 10]. Figure 4 shows the polarization as a function of the angle (given here as lunar phase). The polarization is negative at low angles with a minimum at 11 degrees and exhibits a cross-over from negative to positive at 23 degrees. Polarization curves of this type are not obtainable from natural terrestrial substances. The importance of this curve of the moon is that it has to be reconciled with other very contradictory and unusual characteristics.

Additional conclusions can be drawn from the analysis of the polarization of the earth light as reflected from the night side of the moon. The polarization of light by the lunar surface is small, and the surface tends to "depolarize" initially polarized light.

3. Albedo

The albedo of the moon is quite small -- the most probable value using Bond's definition for albedo is 7 per cent. This low value means that the lunar surface is essentially black. The reason for this is not completely understood. The possibility of partial reduction of metal oxides, especially iron oxides, to a low state of oxidation or to the metallic state by the proton bombardment of the solar wind might cause such low albedo values. However, the type of polarization curve shown in Figure 4 is not in agreement with the possibility of the metallic

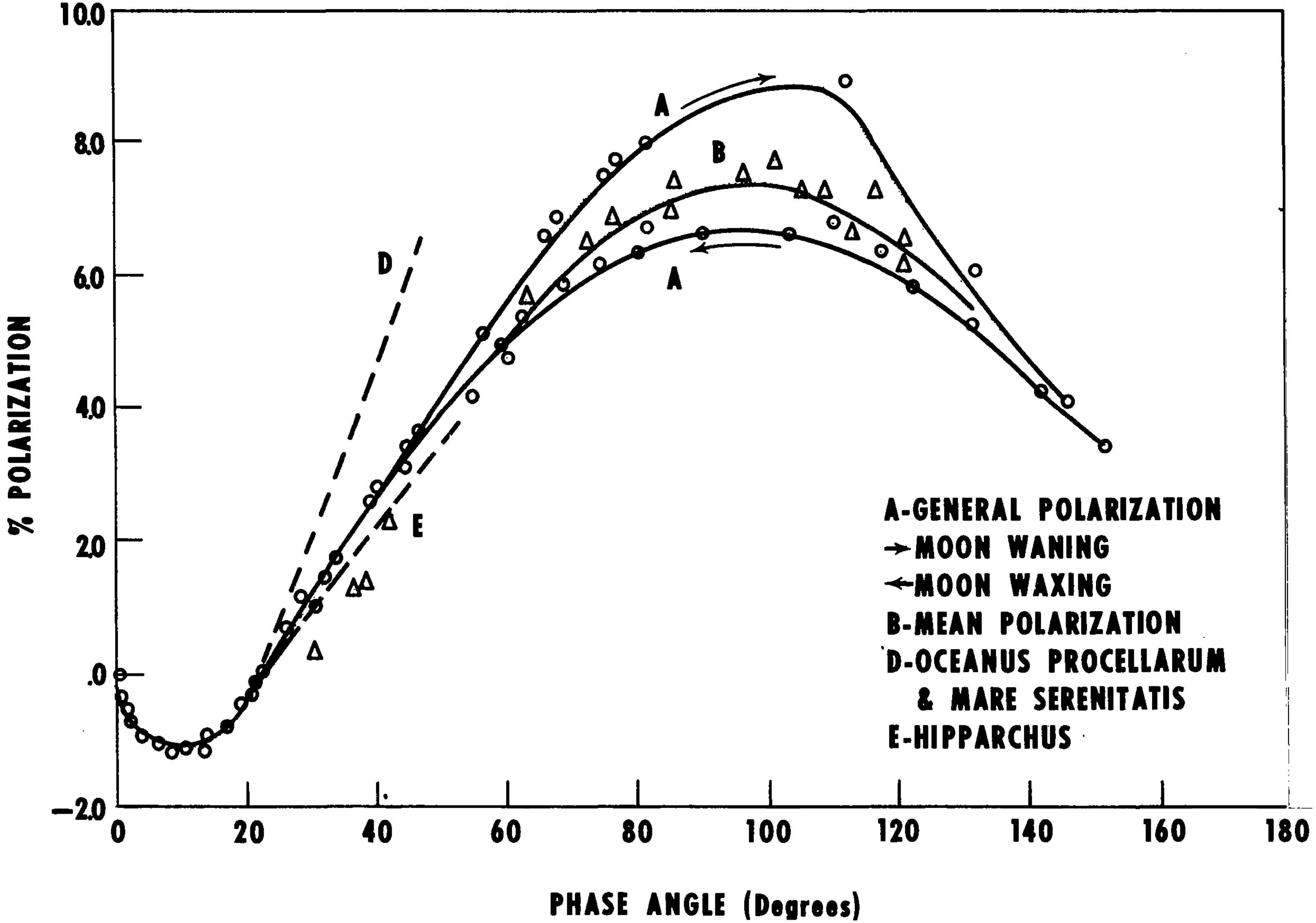

FIGURE 4. THE POLARIZATION CURVE OF THE MOON (AFTER LYOT)

state. On the other hand, due to meteorite bombardment, the presence of meteoritic iron cannot be excluded and should be considered in laboratory studies of simulated lunar materials. In addition, for a non-differentiated moon, the average composition of interplanetary dust has to be considered for lunar surface materials and this again makes the presence of metallic iron and nickel a possiblity. Figure 5 shows the albedo of the moon as a function of the polarization.

The maximum polarization obtained with a substance is related to its albedo: At low albedo values of 15 per cent or lower, the polarization is high. At a normal albedo of 30 per cent and higher, the polarization for terrestrial substances is only a few per cent. It is interesting to note that the lunar surface behaves again differently. It has low albedo combined with low maximum polarization, as shown in Figure 5.

It is worth mentioning that Lyot and Dollfus were able to simulate the polarization behavior of the moon by using pulverized scoria [8]. This consists of a mixture of partially translucent minerals and opaque particles. The fit is quite good (see Fig. 6). However, the fit exists only in one of many properties, and it still has to be proven whether pulverized scoria conforms to the other characteristics of the moon.

4. Color

The color of the moon is also quite different from earth minerals and soils. The color excess is smaller than most terrestrial minerals, and they are a deeper black than the corresponding black terrestrial minerals of similar color. Figure 7 shows the color excess, given according to standard astronomical procedure in stellar magnitude, plotted vs. the albedo [5]. The lunar materials have a much smaller range of variations than the earth materials, and their range of color values extends to smaller albedo values. The small color excess, however, could be partially due to averaging caused by the resolution limit of 550 m.

B. CHARACTERISTICS IN INFRARED

1. Angular Dependence

Measurements in the IR have been made by L. Rosse [11, 12, 13] in 1868 and, more recently, by Pettit and Nicholson [14 to 19]. Our knowledge of the temperatures of the moon depends on measurements in this region of the spectrum. Practically all of the IR investigations have used the atmospheric window between 7 and 13 μ.

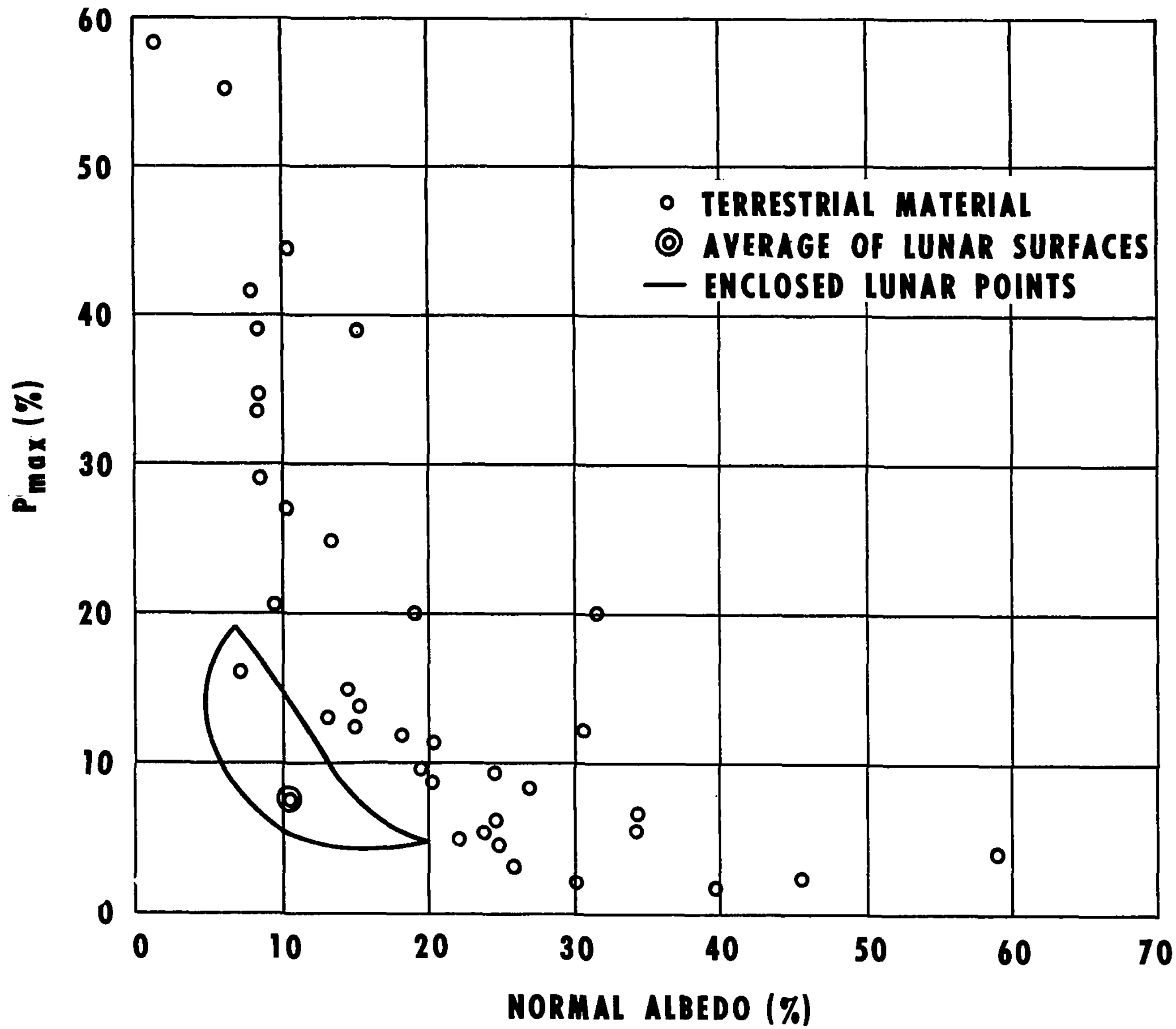

FIGURE 5. POLARIZATION-BRIGHTNESS DIAGRAM FOR LUNAR AND TERRESTRIAL MATERIALS

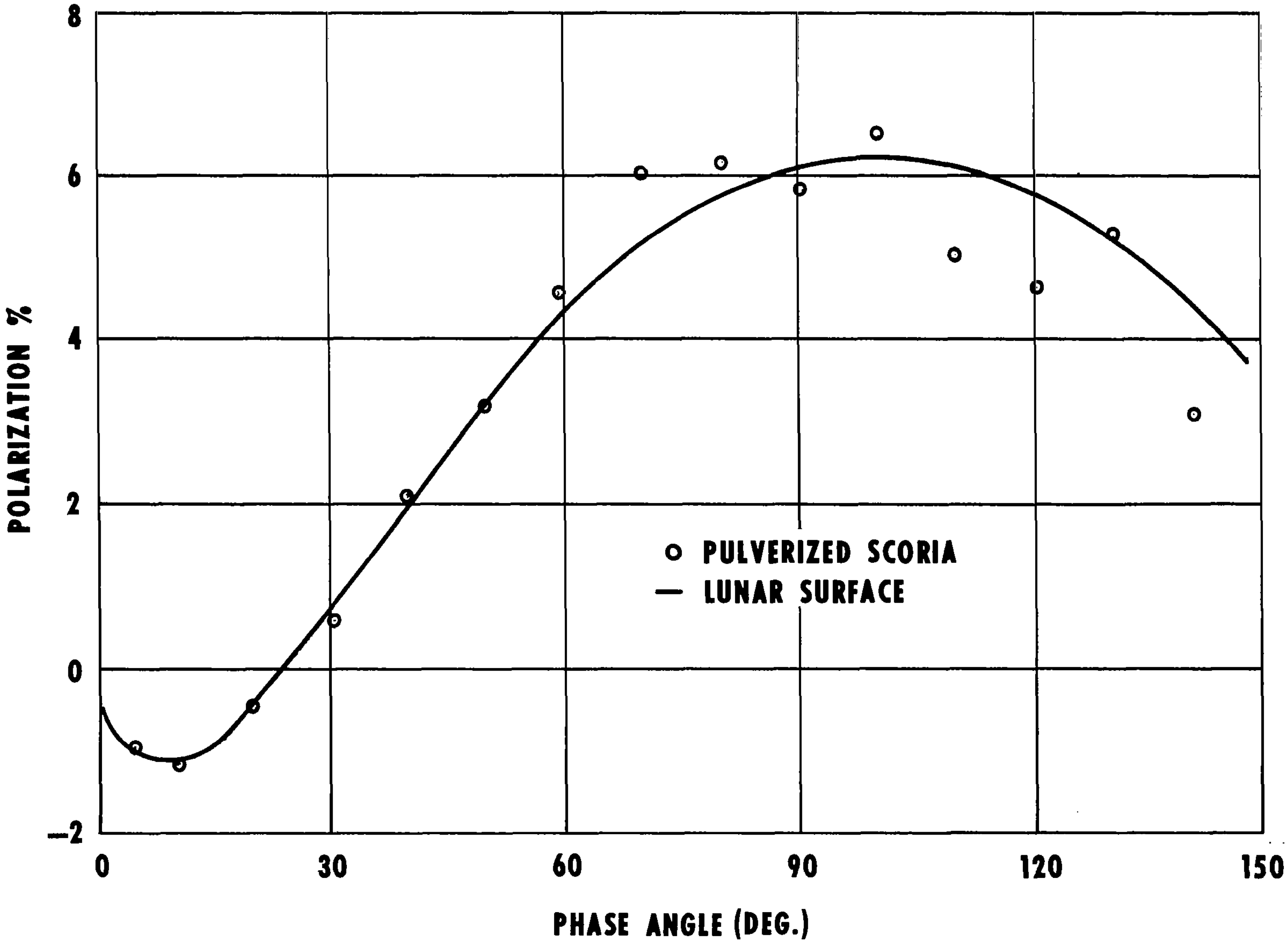

FIGURE 6. POLARIZATION CURVE FOR PULVERIZED SCORIA (AFTER DOLLFUS) AND LUNAR SURFACE (AFTER LYOT)

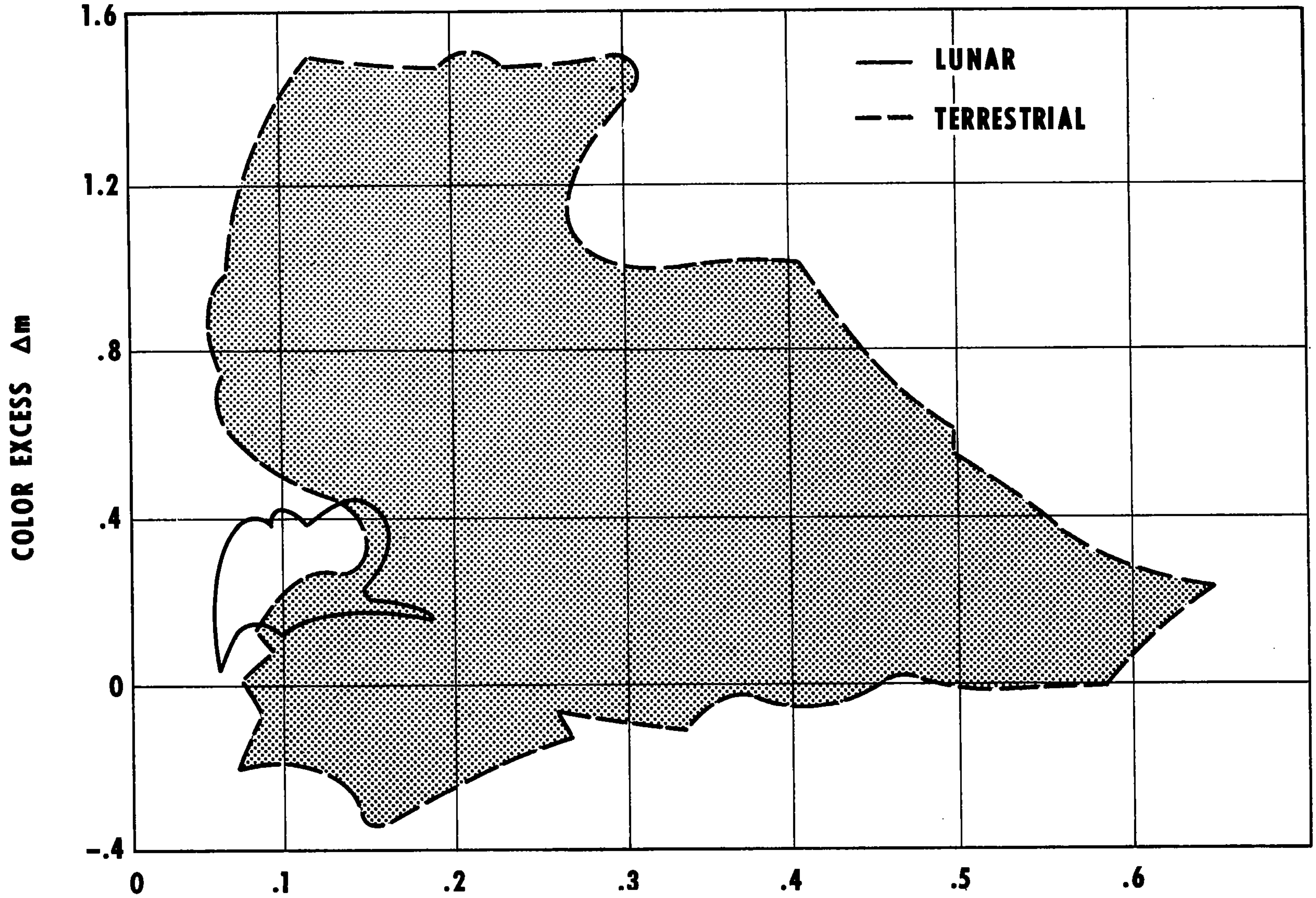

FIGURE 7. COLOR-BRIGHTNESS DIAGRAM FOR LUNAR AND TERRESTRIAL ROCKS (AFTER ORLOVA)

The behavior of the IR radiation coming from the surface of the moon as part of the emitted radiative flux is again quite unique. The angular dependence is different from any known terrestrial surface. Pettit and Nicholson have obtained a cosine 2/3 law for the dependence of the flux on lunar longitude [14]. According to their measurements, this is valid for full moon, but does not apply for other phases of the moon. This derived relationship means that the temperatures computed from the obtained flux measurements are higher when compared to a Lambert surface. The reason for the higher energy fluxes is attributed by all investigators to the roughness of the moon. No consistent model has been found to describe the physical behavior of the moon at the IR wavelengths. More recent investigators such as Sinton have not used this relationship, but instead have used a Fourier series of cosine of the phase angle to describe the lunar temperature [20]. The radiative flux fields as a function of the angle of incidence and the angle of scattered electromagnetic radiation is of considerable interest for a description of the thermal model of the moon, and for equipment placed near or on the surface of the moon. Figure 8 shows the results of IR flux measurements for the subsolar point. So far, all thermal analyses have been based upon the assumptions that the radiation field corresponds to the 2π hemispherical field of a Lambert surface. The actual dependence of the IR radiation from the lunar surface on the angle is not known. The assumption of a Lambert surface which is often used for terrestrial surfaces, if high accuracy is not required, is considered a good approximation, but with the strong deviations known for other properties of the lunar surface, it is very likely not acceptable. At the present time, the lack of knowledge of the angular dependence means a considerable degree of uncertainty for all lunar temperature and radiative transfer calculations. For comparison, consider the discrepancies in the visible region of the spectrum which are somewhat better known. Figures 1, 2, and 3, show how strong the deviations are at the wavelengths of visible light. The maximum deviation for terrestrial substances between total hemispherical and normal emittance is about 5 per cent for dielectrics. For the reflectivity of the lunar surface in the visible region, the deviation is more nearly a factor of 2.

2. Thermal Contour Maps

Most temperature determinations are based upon the assumption that the total hemispherical emittance is known and is close to 1.0. This is one thermal property of the lunar surface which is not known, and Sinton regrets that not enough measurements have been made to determine the angular dependence [20].

Isotherms obtained by Sinton are shown in Figure 9 [21]. The resolution was about 50 km. Other investigators have used higher resolution sensors.

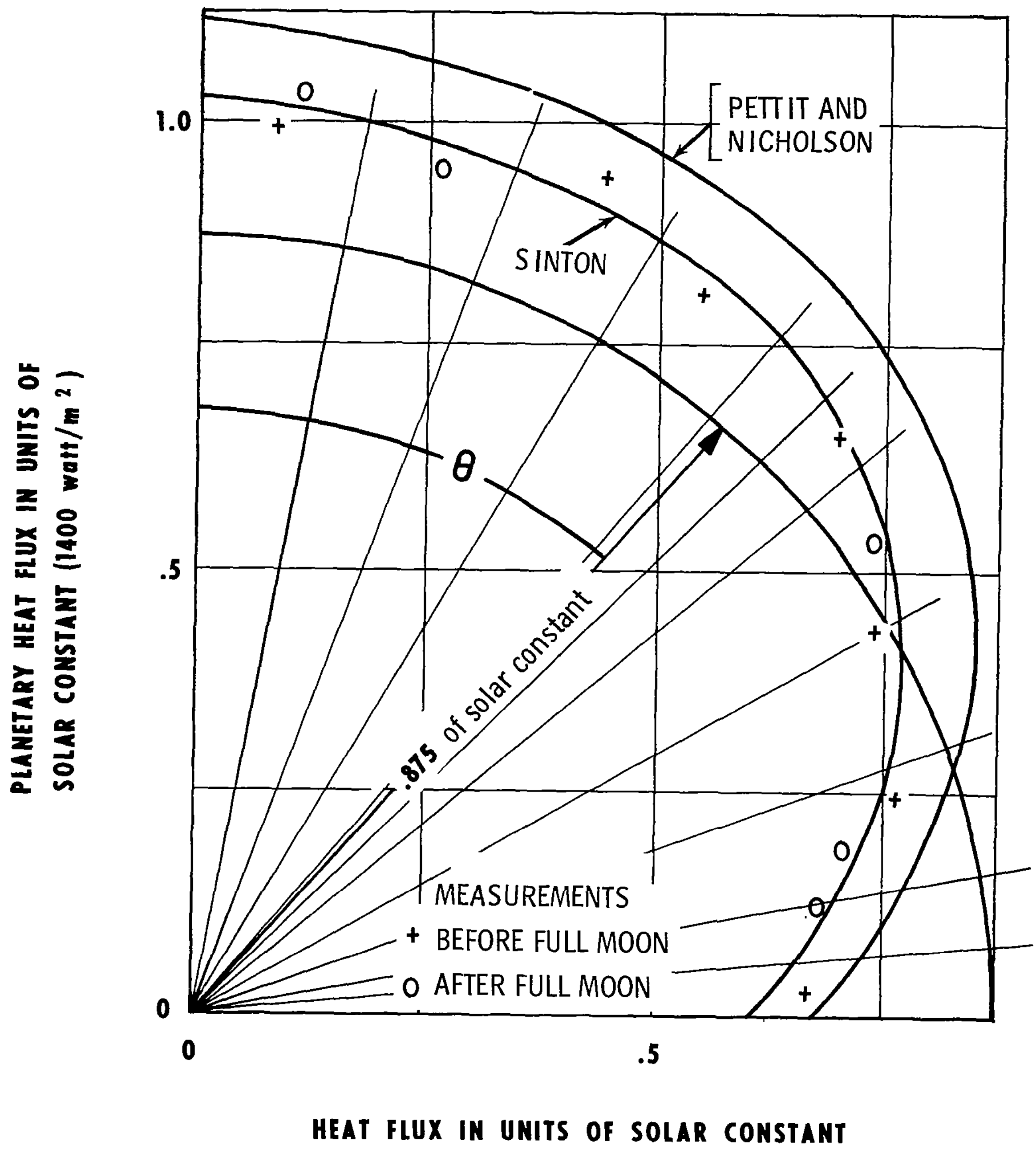

FIGURE 8. POLAR DIAGRAM OF IR FLUX DENSITY AT SUBSOLAR POINT

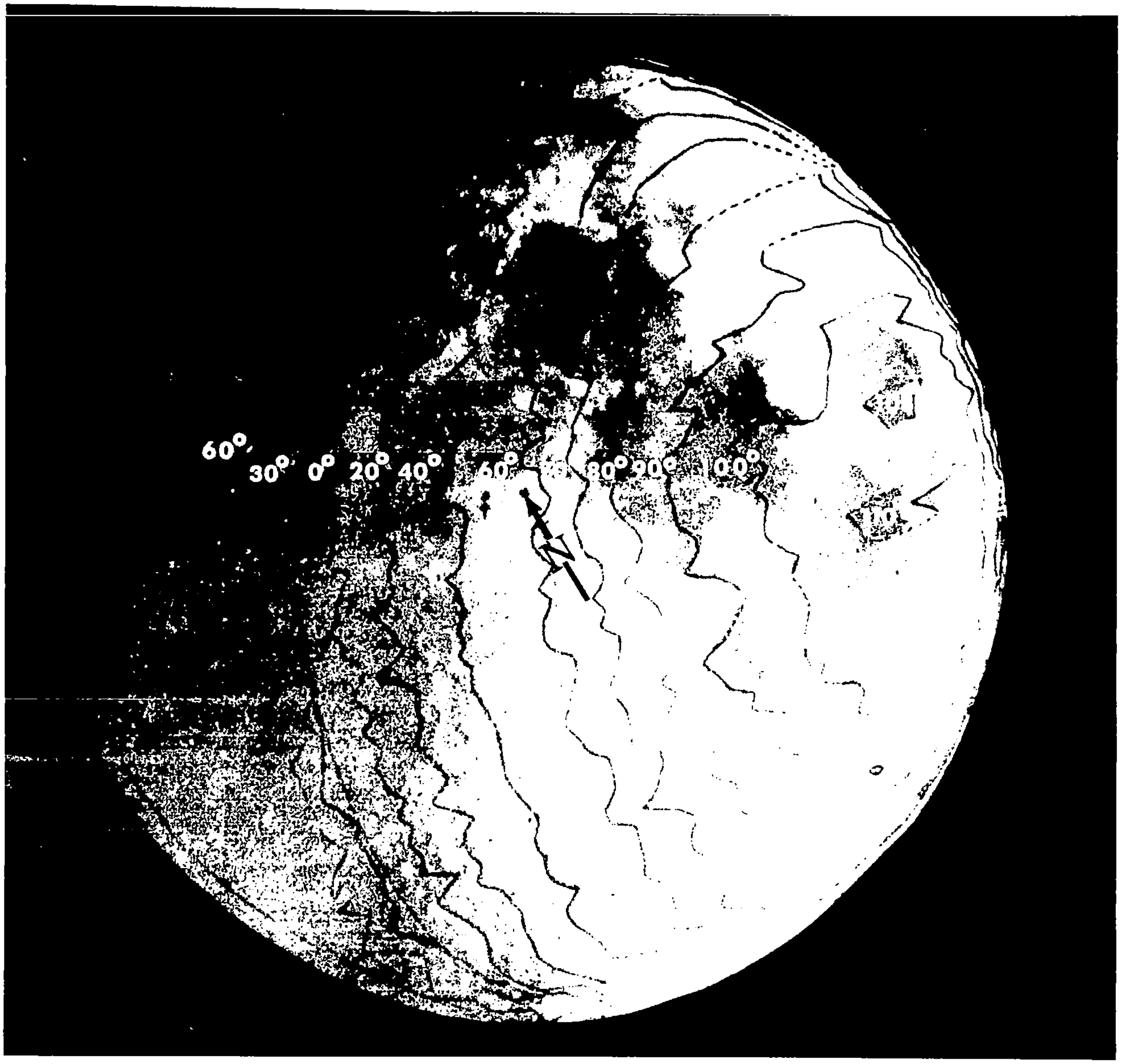

FIGURE 9. MAP OF LUNAR ISOTHERMS ON A SIMULTANEOUS PHOTOGRAPH OF THE MOON

A sensor covering an area of about 15 km diameter on the moon was used by Shorthill and Saari [22]. Even at such resolution, the IR picture of the moon deviates considerably from the optical picture. The craters do not always show as prominent features; however, some unexpected characteristics have been discovered. Some of the craters are colder during lunar day and warmer during lunar night than their surroundings, as found by Shorthill, Borough and Conley [23]. This is especially true for the young crater Tycho.

All other features of the moon have nearly the same characteristics in the IR. Only small distinctions exist between maria, mountains, rays of craters, etc.; however, shadows show up near the terminator and in craters.

The curve of lunar temperature by Pettit and Nicholson [14 - 19] is shown in Figure 10. From their observations, they derived a temperature dependence such that the energy flux varies with cosine $^{2/3} \alpha$. Most thermal models of the moon introduce this as a phase function in addition to the dependence on angle of incidence and angle of scattered radiation. More analytical work is necessary as well as experimental work in the laboratory and by ground-based lunar measurements (this includes balloon measurements). However, values are available for the angular dependence of radiation flux coming from the subsolar point (Fig. 8). A 2π integration yields a value of .90 for the ratio of total to normal emittance. The normal emittance of the subsolar point is unknown. Computation by formulae applicable to dielectrics yields values slightly below 1.0. However, due to the roughness of the lunar surface, the applicability is not well established. One additional handicap in the analysis is the fact that all measurements have been made in a small IR band which is not necessarily representative of the whole spectrum. If we adopt the most likely value of .93 for the complement of the lunar albedo with respect to the whole solar spectrum, and an estimated value of .95 for the normal IR emittance ϵ_T, we obtain for the temperature of the subsolar point a value of 405°K. If we assume for the total normal emittance a value of .99, the temperature would be 400°K. Since the other inputs for this calculation are well established by measurements, the range for the temperature of the subsolar point is 400 to 405°K. The author accepts 405°K as the most probable mean value, pending further investigations of the normal emittance. Due to local differences of lunar albedo, the temperatures will vary around this mean value. For a minimum local albedo of .05 (Fig. 7) the temperature is 407°K, for the highest albedo of .15 the temperature of the subsolar point becomes 396°K. Lower temperatures than 390°K can be explained only if the total normal emittance is higher than 100 per cent, e.g., as shown in Figure 8. This situation requires further investigations.

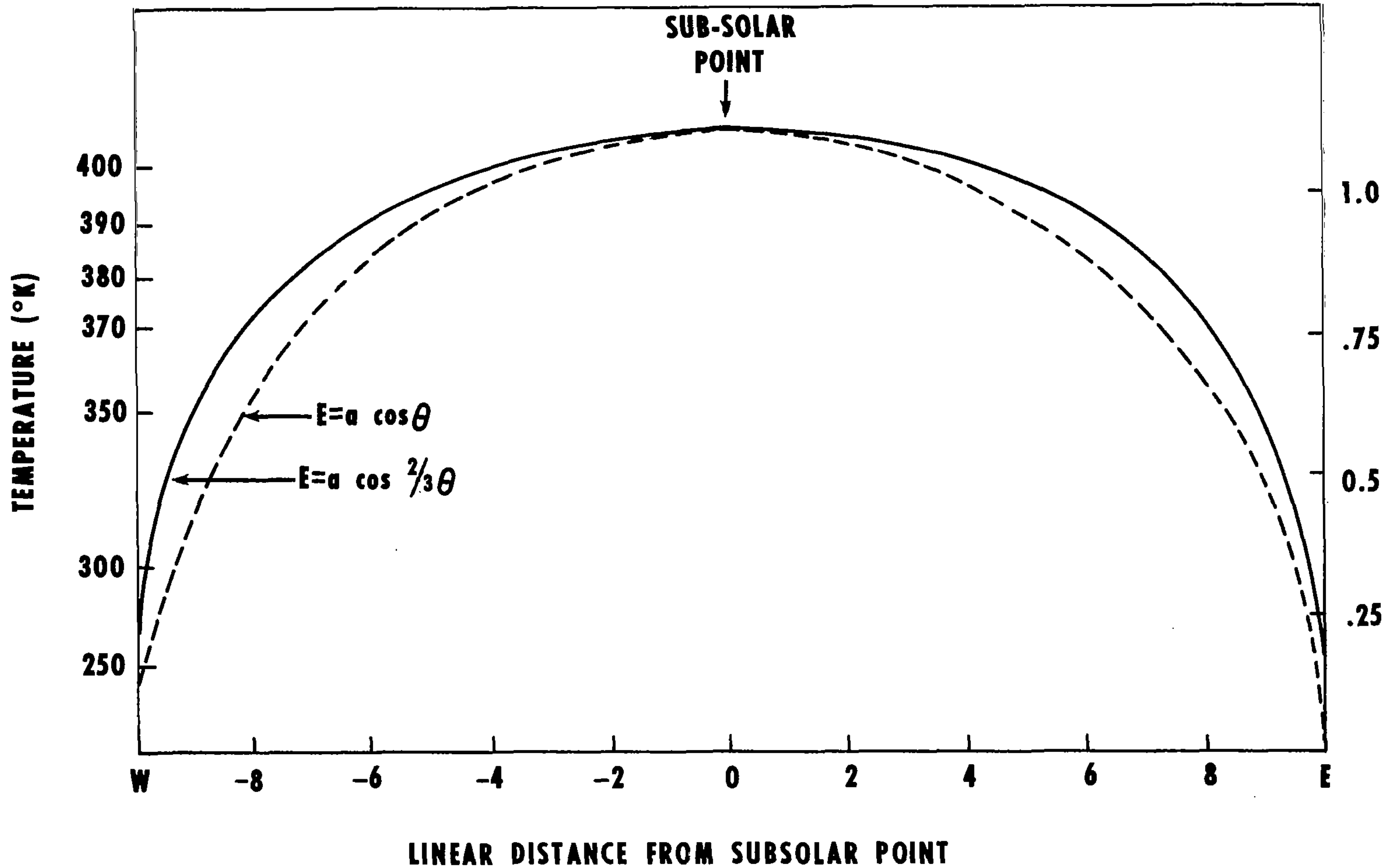

FIGURE 10. DISTRIBUTION OF PLANETARY HEAT FLUX OVER THE DISK AT FULL MOON

3. Cooling Transients

In all infrared work, considerable additional information can be gained by analyzing transients. In the case of the moon, two types of transients are important: the lunations, and the eclipses. Most of the existing thermal models of the moon have been derived from this type of investigation. W. Snoddy has used transients for evaluation of temperature measurement for satellites [24]. These techniques are equally applicable to the lunar temperature transients.

The average temperature of the moon can be computed by integrating sub-surface temperatures over the whole lunar surface. Temperatures of about 229°K have been obtained [25], and some RF measurements agree with this value. During the lunar day, the interior of the crust serves as a heat sink, with energy flowing from the surface toward the interior. During the lunar night, the interior serves as a heat source. This flow of heat maintains the surface at a temperature of approximately 80 to 100°K. The source of the energy is internal radioactivity and the energy that flows in during the day.

Lunar thermal models have been derived from four types of measurements: (1) lunar night temperature (2) slope of lunar night temperature decrease (3) lunation transients and (4) eclipse transients. The derived models are not necessarily the same, but instead of describing the differences, this paper will point out the features that are clearly established from the measurements, which are again unique, and found only on the moon (also expected to be found on Mercury and the planetoids): (1) the surface of the moon has very low thermal diffusivity (2) the characteristic thermal quantity $(k \rho c)^{1/2}$, called thermal admittance, which is related to the time constant of thermal transients, is unusually low. The value for the lunar surface is 1/50 of that of a typical terrestrial soil surface. Thermal diffusivity and thermal admittance values of powders in vacuum were studied by members of the Research Projects Laboratory of Marshall Space Flight Center and A. D. Little, Inc. under contract to MSFC. Values equal to those on the moon were measured in tests with fine powders of perlite, which were carefully prepared under hard vacuum conditions [26]. Again, the correlation of one lunar property with one material in the laboratory does not mean that the exact composition of the moon's surface is known.

The following lunar models based upon thermal analysis have been discussed in the literature, and correlation has been made with specific sets of measurements:

(1) A surface layer of the moon of 2 mm with a value of $(k \rho c)^{1/2}$ of 40 $\frac{\text{Joule}}{m^2 \deg \sqrt{\sec}}$; under this, there is solid rock like basalt.

(2) A surface layer of a few mm with low $(k \rho c)^{1/2}$, a second layer of several cm thickness with a value higher by a factor of 10, and solid rock underneath.

(3) A surface layer with 90 percent of the area consisting of under-dense material and the balance of 10 per cent covered with larger grains or boulders. This model attempts to resolve some discrepancies between the cooling transients of lunation, the cooling transients during the early portion of eclipses, and the shallower slopes after the initial sharp drop.

(4) No layers, but a structure of very under-dense material. The density and the size of particles increase with depth. At a depth of 1 m, the structure of divided particles is still under-dense by approximately a factor of 3.

The layer models are quite popular. All mathematical models found in the literature use simple one-dimensional analysis. In all cases only one mode of heat transfer is used. Some mathematical analyses done in the Research Projects Laboratory of MSFC by L. Russell [25] have shown that there is no proof for the layer models. The measurements obtained so far are not accurate enough to decide upon a specific thermal model. The most likely model which deserves more thorough study is (4) above. This model is being used at the present time, but may be subject to changes or improvements based upon further investigations.

4. IR at Various Wavelengths

Measurements of thermal radiation are hampered by the opaqueness of the earth's atmosphere for most of the IR spectrum. Figure 11 shows three curves of radiative energy flux in joules/micron. The upper curve is the radiation from the atmosphere corresponding to a black body radiating at 220°K. An atmospheric window exists between 7.5 and 13 microns, with some ozone bands near 9.5 microns. Increased accuracy can be obtained by narrow band IR filters. Two bands are shown in Figure 11, one from 8 to 9.3 microns, and another from 10 to 12.5 microns. The middle curve is the energy flux coming from a lunar black body with a temperature of 389°K, and the lower curve from a spot on the night side of the moon with a black body temperature of 100°K. In the lower curve, the integrated radiative flux in the 8 to 9.3 micron band is 2.1×10^{-4}, and in the 10 to 12.5 micron band it is 2.9×10^{-3} times the total flux coming from a 50 km diameter area of the moon at 100°K blackbody temperature.

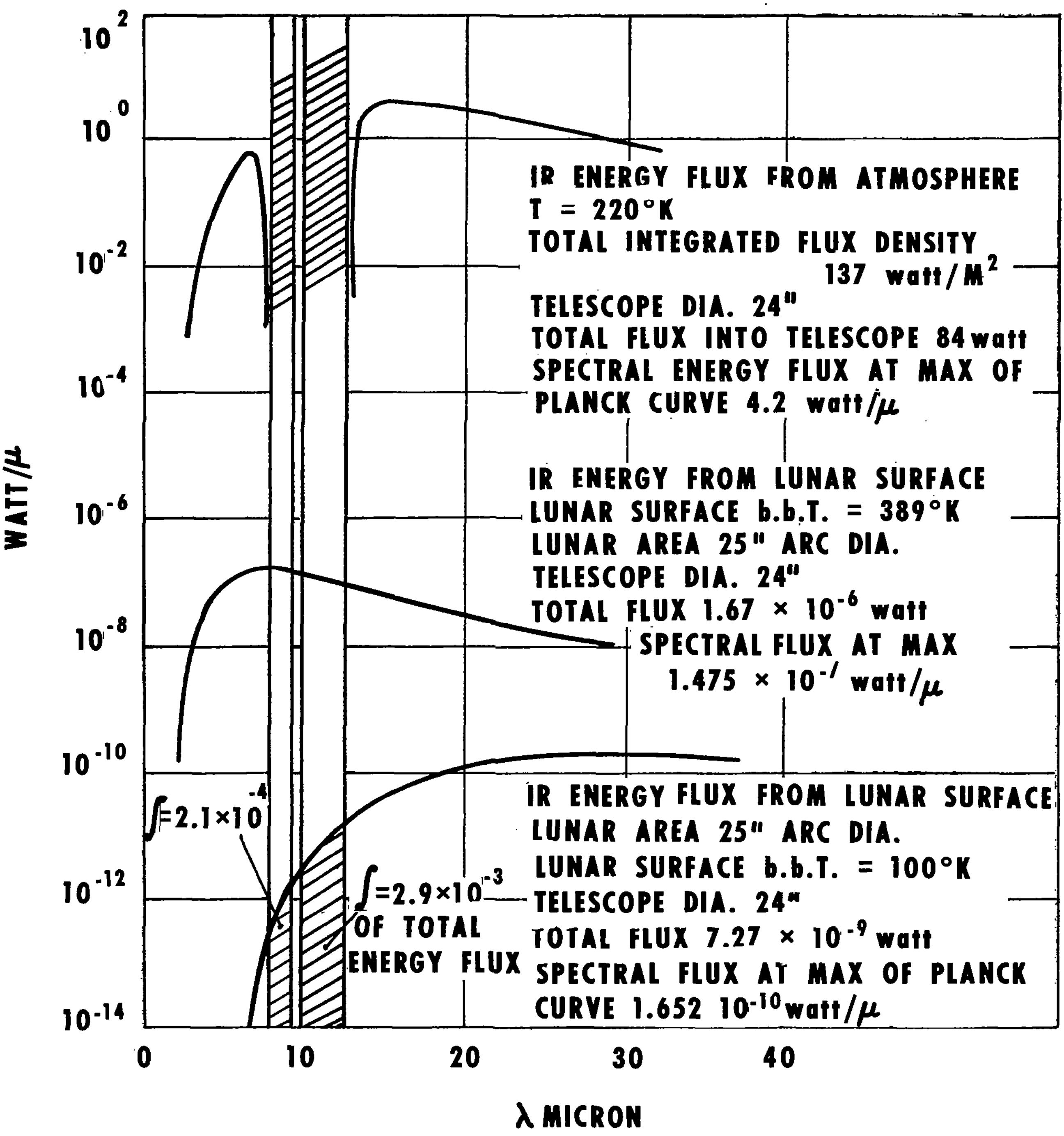

FIGURE 11. IR ENERGY FLUX FROM MOON AND ATMOSPHERE

If measurements could be obtained above most of the atmosphere, it would be possible both to reduce the background radiation and to open up other IR windows, e.g., one around 20 to 24 microns. One could use wideband filters and determine a color temperature by using principles of pyrometric temperature determinations in the IR.

RF MEASUREMENTS

Thermal analysis done recently by L. Russell [25] shows how the solar heat in a lunar day-night heat cycle travels as a heat wave into the lunar interior. The analysis is suitable for:

(a) Planning for thermal experiments during lunar exploration

(b) Evaluation of electromagnetic thermal waves at RF bands. (Since this radiation comes from layers well below the surface, a correlation with thermal heat waves can be made.)

Figure 12 shows a curve such as that obtained by Russell [25]. The cyclic variation of the surface temperature has been introduced as a boundary condition by use of the well known Sinton curve. The thermal diffusivity α has been used as a variable parameter in the study. Figure 12 shows the computed results for an α value of 10^{-5} m^2/sec.

Because of the capability to obtain measurements from various layers of the moon below the surface, we have additional information with which to derive a thermal model. This thermal model has to be consistent with the thermal radiation measurements at mm wavelengths.

Due to the greater penetration depth with increasing wavelength, the lunar RF temperatures show less time variations and a greater phase shift with increasing wavelength. Figure 13 shows measurements by Gibson [27] at 8.6 mm, and an analytical curve based on Jaeger [28, 29].

Results of measurements at various wavelengths can be included in the existing MSFC thermal computer programs for thermal design purposes. A computer program applicable to thermal radiative transfer to lunar surface craft is presently being developed by W. Snoddy and J. Zwiener of Research Projects Laboratory of MSFC.

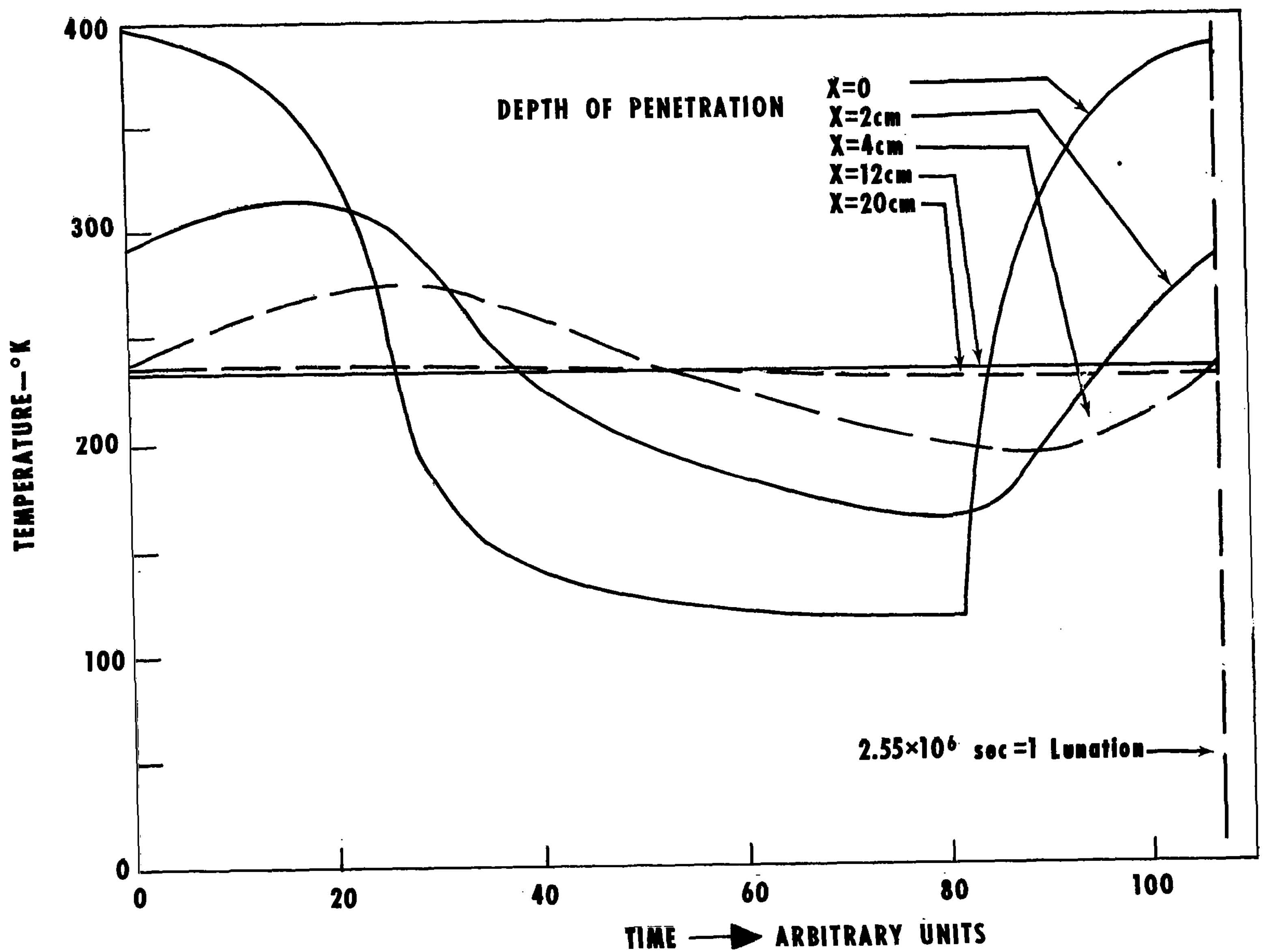

FIGURE 12. TEMPERATURE OF LUNAR SURFACE AND SUBSURFACE VERSUS TIME WITH $\alpha = 10^{-5}$ cm^2 / sec

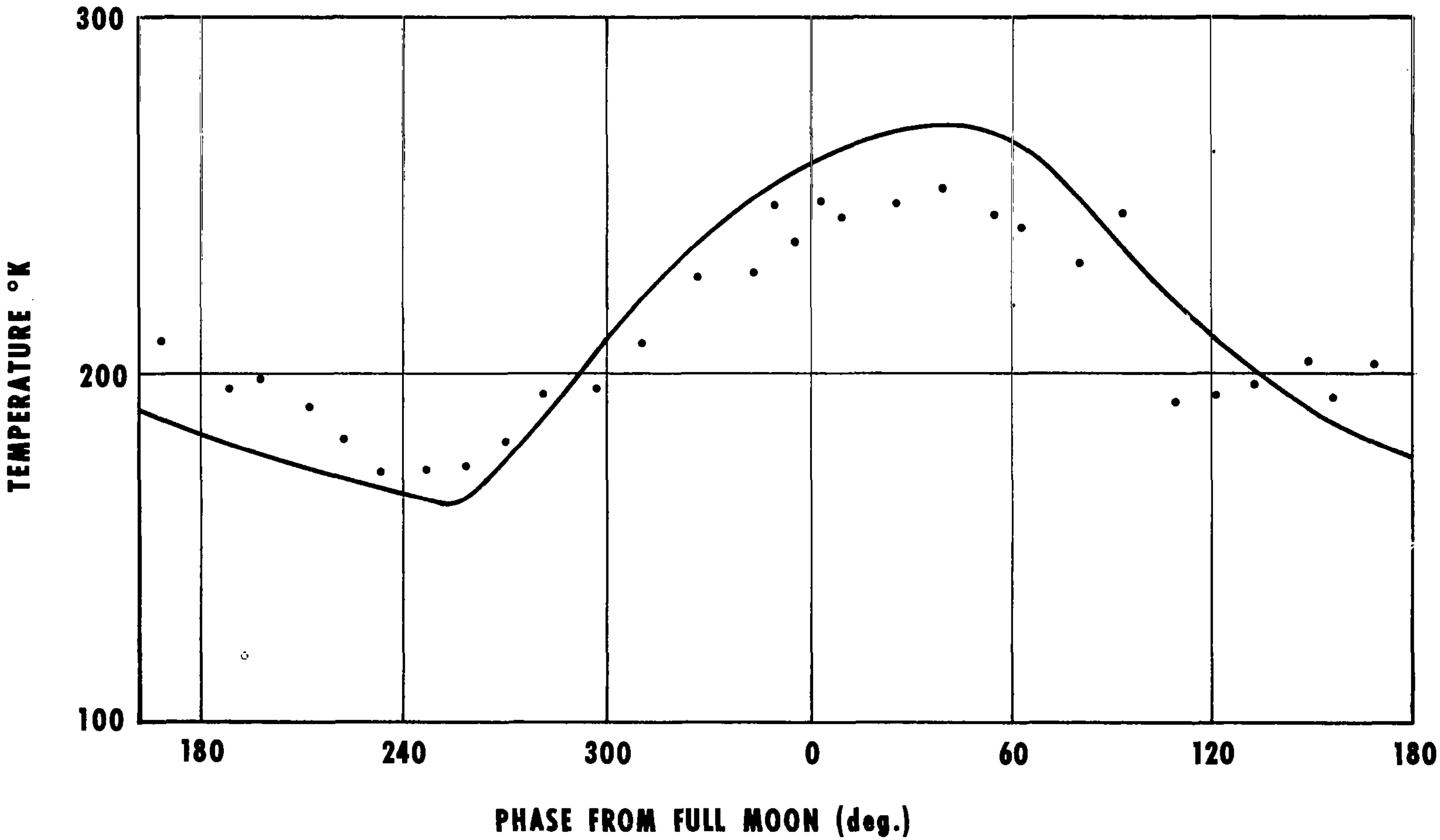

FIGURE 13. GIBSON'S OBSERVATIONS OF LUNAR TEMPERATURES AT 0.86 cm COMPARED WITH JAEGER'S THEORETICAL CURVE HAVING $(k\rho c)^{1/2} = 42$ AND C = 125 (C IS A DIMENSIONLESS NUMBER, $C = (\frac{\mu}{\rho})(k\rho c)^{1/2} P^{1/2}$)

SUMMARY AND CONCLUSIONS

What can be stated about our knowledge of the moon based upon the results of present investigations? This question can be answered in the following way:

(1) Every surface spot of the moon shows the same unique characteristics in the visible band of the solar spectrum:

Backscatter

Polarization

Lack of color

Low albedo

Deviations from these general characteristics of the lunar surface are small. No natural terrestrial substances which have the same properties exist. Not enough is known about other portions of the solar spectrum (such as UV, solar IR), and more measurements in these wavelength regions are needed.

(2) Thermal IR measurements have been made only in the atmospheric window between 8 and 13 microns. A general characteristic is the strong angular dependence. This angular dependence is, in turn, a strong function of phase angle. It is also a function of latitude. With this respect, it differs from the visible results. These optical characteristics in the IR are generally explained by the surface roughness, or rather micro-surface roughness of the moon. Detailed measurement of the angular dependence is available only at the subsolar point. Because of the effect of IR radiation on lunar surface craft, lack of knowledge in this area is most critical.

Cooling transients of IR measurements have revealed that the lunar surface has a high thermal inertia. A considerable uncertainty still remains between cooling transients of lunation and those of eclipses. There is a difference of cooling transients for ten "young" craters, including Tycho. It is interesting to note that this difference shows up at IR wavelengths, whereas no such difference occurs in the visible.

(3) If the moon is viewed at increasing wavelengths, one obtains additional and quite different information:

(a) The resolution is proportional to the wave number and, therefore, the size of resolvable objects goes up with wavelength.

(b) One is looking deeper into the lunar crust

(c) The measurements become sensitive to phase angles and are affected by librations

The thermal radiation in the mm wavelength window of the atmosphere measures the temperatures below the surface. The amplitudes of the periodic temperature curve are smaller, and one observes a phase lag. Mean temperatures are in fair agreement with computed values.

Cooling transients are different from lunation and eclipses.

Angular dependence reveals roughness of surface.

(4) If one goes from mm waves to larger wavelengths, the thermal energy flux is not sufficient. In this area, radar reflection measurements have furnished additional information. The moon appears smooth at small angles of incidence. However, near the limb, it appears rough again. Some investigators have derived a similar angular dependence as obtained in the IR by Pettit and Nicholson for radio wave reflection near the limb.

Temperatures derived from radio reflection measurements vary between 170 and 370°K. Based upon the analysis discussed before, the lower values of this total scatter band seem to be more probable. The accuracy is not sufficient to prove or disprove a specific temperature. The main difficulty is that the reflectance is not known, and this is a function of the refractive index and the surface roughness. Also, the composition will have a strong effect, especially if metallic iron and nickel are present. However, one qualitative result is important for the thermal analysis of the moon--the temperatures vary little, or not at all, with the lunation. No effects of eclipses are noticeable in the temperature determination. This means that one is looking deep enough into the crust so that the temperature fluctuations have decreased to negligible or immeasurable amplitudes.

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THERMAL PROPERTIES OF THE MOON AS A CONDUCTOR OF HEAT

By

Billy P. Jones*

INTRODUCTION

Visualize the sun's rays streaming onto the moon's surface, over the period of a day-night cycle, while the moon itself radiates energy out to space due to its own temperature. Most of the sun's energy is absorbed at the surface; a small amount of it is reflected; an even smaller amount is conducted into the crust. The amount of heat conducted into the crust per unit time at the subsolar point is less than one per cent of the amount of heat absorbed and re-radiated at the surface, but this is not true at the limb where the heat conducted through the crust is of the same order as the surface radiation. There have been a number of analyses of the heat conducted through the lunar crust, with some interesting results. This discussion is primarily a review in this area.

WESSELINK'S ANALYSIS

In 1948 Wesselink [1] made a study of the heat conduction into the lunar crust and compared the results with infrared surface temperatures based upon measurements by Pettit and Nicholson [2] for an eclipse. The model represented heat conduction in a semi-infinite solid with solar insolation and radiation at the surface, with the boundary condition of earth-darkening during an eclipse. The roughness of the lunar surface was neglected, and the moon was assumed to be black with respect to infrared radiation. The applicable set of equations was solved numerically, using the Schmidt finite difference method. Figure 1 shows a comparison of the calculated surface temperature near the center of the disk with Pettit's measured data for the eclipse of October 28, 1939. For the calculation Wesselink adopts 370°K as the surface temperature at the subsolar point. This was the value found by Pettit for the temperature near the center of the lunar disk at full moon--just before the beginning of the 1939 eclipse. In order to make the calculations, the thermal admittance has to be assumed. (Thermal admittance is the square root of the product of thermal conductivity and volumetric

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G.M.T.	A	T_o OBSERVED	T_o' $(kc)^{1/2}=43.21$	T_o'' $(kc)^{1/2}=37.81$	T_o''' $(kc)^{1/2}=000$	G.M.T.	A	T_o OBSERVED	T_o' $(kc)^{1/2}=43.21$	T_o'' $(kc)^{1/2}=37.81$	T_o''' $(kc)^{1/2}=000$
h. m						h m					
3 24	1081	370	370	370	371	6 01	0.0	188	192	188	0
41	1081	368	370	370	371	08	0.0	186	189	184	0
55	1081	368	370	370	371	16	0.0	184	187	182	0
4 10	1081	370	370	370	371	26	0.0	182	184	179	0
25	998.6	360	364	364	363	38	0.0	181	182	177	0
31	918.4	356	357	357	356	52	0.0	180	179	174	0
37	829.8	348	349	349	347	7 05	0.0	178	177	172	0
44	687.6	331	336	336	331	20	0.0	177	174	169	0
49	583.7	324	324	324	318	29	0.0	176	173	168	0
55	455.4	306	309	309	299	39	0.0	177	171	167	0
5 01	343.8	293	294	294	278	45	11.9	182	171	166	119
04	283.1	294	285	285	265	52	70.4	210	189	185	188
08	212.0	269	272	270	247	8 07	302.6	250	248	252	270
14	122.0	258	254	250	215	14	438.6	286	279	281	296
20	50.9	244	235	229	173	23	625.5	310	310	311	323
30	0.0	198	213	205	0	33	819.4	336	336	336	346
35	0.0	197	207	200	0	44	986.0	363	354	354	362
42	0.0	194	201	195	0	9 14	1081	373	369	369	371
48	0.0	194	197	192	0	32	1081	374	369	369	371
54	0.0	190	194	190	0						

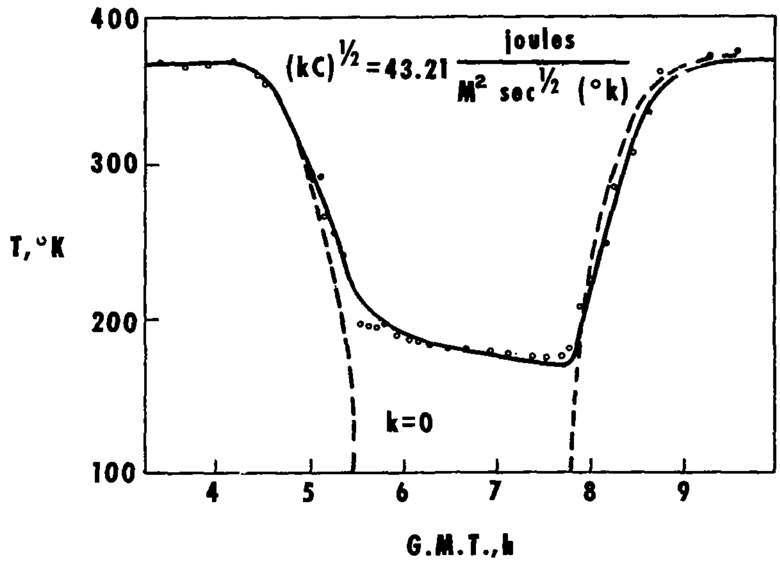

FIGURE 1. TEMPERATURE NEAR CENTER OF LUNAR DISC DURING ECLIPSE (OCTOBER 28, 1939)

heat capacity. The reciprocal is called thermal inertia.) The solid curve in the figure is calculated using a thermal admittance of 43.21 Joules M^{-2} $sec^{-\frac{1}{2}}$ $(°K)^{-1}$. The start of the eclipse was 4^h04^m G. M. T. Pettit's measured data are shown as open dots. The dotted curve is the calculated temperature for zero thermal conductivity, using a simple balance between solar radiation and the Stefan-Boltzmann law. The computed slope during totality (see 6^h to 7^h G. M. T. on abscissa) is slightly steeper than the observed data indicate. Parametric variation of thermal admittance was tried to remedy this, but it could not be improved without spoiling the fit in other portions of the curve. The table shown in the figure gives the measured temperatures for three different values of thermal admittance. The column labelled "A" is the absorbed solar radiation in watts/M^2. It should be noted that the value of A before the eclipse, 1081 watts/M^2, does not correspond to one solar constant. The difference is assumed to be reflected. The value of 1081 was derived by Wesselink. However, he takes one solar constant of incident radiation to be 1324 watts/M^2, and we know from more recent data that the solar constant should be nearer 1395 watts/M^2. Even so, his estimated reflectance is fairly high, being about 20 percent. His derived value for A of 1081 is based upon the temperature of the subsolar point just before eclipse of 370°K. The time dependent values for A shown in the figure are based upon calculations of the fraction of the sun's energy taken away from the moon by the earth during the eclipse, taking account of limb-darkening by using established formulae. Wesselink adopts the value of thermal admittance used for the solid curve in the figure as being the one most probably representing the lunar crust. He attempts to correlate this value with some likely terrestrial materials. He examined a list of 140 substances which were poor conductors of heat and could not find one whose thermal admittance was low enough. He compared with Smoluchowski's data on 15 powders in vacuum and found a fair correlation for 11 of these which had a grain size smaller than 0.1 millimeter.

JAEGER'S ANALYSIS

In 1950 Jaeger and Harper [3] also made an analysis of the Pettit and Nicholson data for an eclipse. Their results were in good agreement with Wesselink's, their value for thermal inertia being 2.45×10^{-2} $Joules^{-1}$ $M^2(sec)^{\frac{1}{2}}$ (°K). They also found the greatest discrepancy in the umbra portion of the shadow. Two possible explanations were advanced for this. Jaeger and Harper (1950) and Lettau (1951) point out that this effect could be explained by an increase in thermal conductivity with depth--or with temperature. Jaeger and Harper, in their 1950 paper, examine the case of thermal conductivity increasing with depth by considering a two-layer model. The top layer is supposed to be a thin layer of dust over a substratum of rock or other material. They find the best fit to be 2 millimeters thickness of dust on a substratum with a thermal inertia of 2.45×10^{-3} Joules^{-1} M^2 $(\text{sec})^{\frac{1}{2}}$ (°K).

In 1953 Jaeger [4] made an analysis of the Pettit and Nicholson data for a lunation. Jaeger abandoned the Schmidt method for this problem and presented his own numerical method in a separate paper, applicable to problems of the periodic type [5]. Figure 2 shows the result. The parameter D is used, where $(k \rho c)^{-\frac{1}{2}}$ in the numerator applies to the substratum and the d/k' applies to the thin top layer:

$$D = \frac{T^{\frac{1}{2}} (k \rho c)^{-\frac{1}{2}}}{d/k'}$$

The dotted curves are for a thermal inertia of the substratum of 2.99×10^{-3} Joules^{-1} M^2 $\sec^{\frac{1}{2}}$ °K and the solid curves for a value of 4.78×10^{-4}. Decreasing D tends to lower the curves and flatten them. Table I shows some corresponding thicknesses of the dust layer. These thicknesses are based on a thermal inertia of the dust layer of 2.39×10^{-2} Joules^{-1} M^2 $\sec^{\frac{1}{2}}$ °K. The specific heat is assumed to be 837 Joules/kg °K and the density is taken as 1800 kg/M^3. In all cases the thickness is less than 1 centimeter.

LETTAU'S ANALYSIS

In 1951 Lettau presented an analysis based upon special assumptions regarding the depth and time dependency of the thermal properties [6]. A number of models are discussed. In one the thermal diffusivity is assumed to be a linear function of depth. In another, thermal diffusivity is a time function. He gives a crude estimate, based upon comparison with the 1939 eclipse data, that the top layer of powder-like material is about ½ meter thick.

In 1962 Lettau analyzed a new model [7]. This time he assumed that the conductivity, thermal diffusivity, and volumetric heat capacity have their lowest values at the surface and approach continuously and asymptotically conditions of homogeneity for increasing depth. His comparison of the theoretical results with observational data is based upon the interrelationship between amplitude decrement and phase lag of the heat wave generated at the surface during a lunation. The observational data used in the comparison is shown in Table II. It shows data from various sources as a function of wavelength ranging from 8

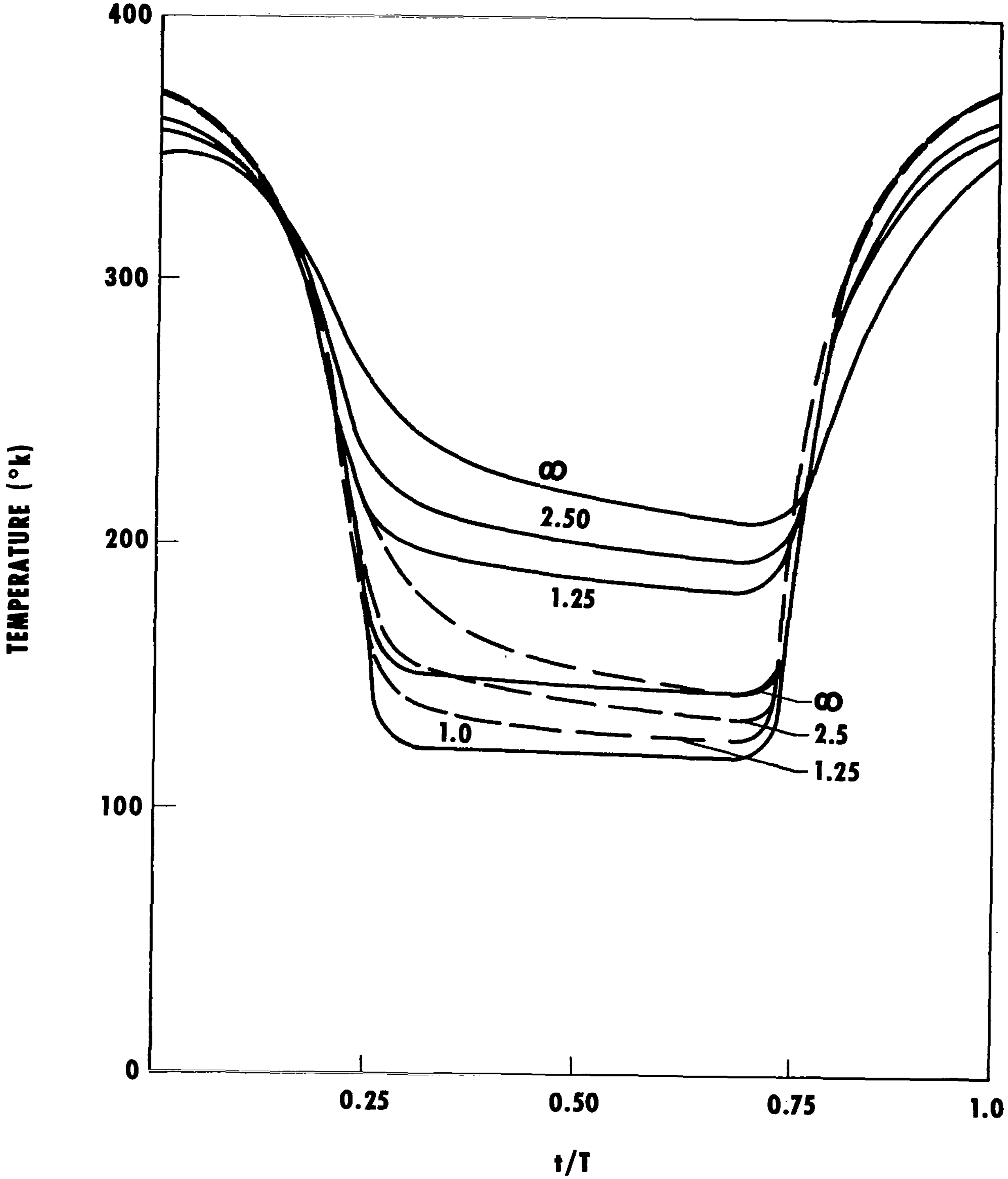

FIGURE 2. SURFACE TEMPERATURE OF A SOLID

TABLE 1 THICKNESS OF DUST CORRESPONDING TO VARIOUS VALUES OF D AND $(kpc)^{-1/2}$

D \ $kpc^{-1/2}$	5.98×10^{-3}	2.99×10^{-3}	4.78×10^{-4}
2.5	0.45	0.22	0.04
1.25	0.89	0.45	0.07
0.625		0.89	0.14
0.25			0.36
0.1			0.89

TABLE 11 SUMMARY OF LUNAR TEMPERATURE DATA DETERMINED FROM MEASUREMENTS OF INFRARED AND MICROWAVE RADIATION

	WAVELENGTH	MEAN TEMP. T_m, °K	AMPLITUDE	PHASE-LAG	a/T_m
PETTIT & NICHOLSON	8 TO 14 μ	247	127	—	0.52
AMENITSKIY	1.5 mm	250	100	—	0.40
SALOWONOVICH	8 mm	197	32	40	0.16
GIBSON	8.6 mm	180	30	39	0.17
PIDDINGTON & MINNETT	12.5 mm	249	52	45	0.21
ZELINSKAYA	16.3 mm	224	36	—	0.16
GREBENKAMPER	2.2 cm	200	15	—	0.08
TROITSKY & ZELINSKAYA	3.2 cm	170	12	—	0.07
AKABANE	10 cm	315	36	45	0.11
MEZGER & STROSOL	20.5 cm	250	5	—	0.02
WESTERBOUT	21 cm	170	0	—	0.00
DENISSE & LaBOUX	33 cm	189	19	—	0.10
SEEGER	75 cm	186	0	—	0.00

microns to 75 centimeters. There is considerable scatter in the temperature data. Some of this is because in some cases the data is for a limited area of the disk, while in others the whole disk is represented. However, the last column on the right, amplitude-temperature ratio, appears to be systematic with wavelength. Lettau compares the amplitude-temperature ratio and phase lag with his theoretical calculations. Table III summarizes the result. The uppermost 2 centimeters have a very low diffusivity and a significantly reduced volumetric heat capacity. In the 2- to 6-centimeter layer the volumetric heat capacity reaches its homogeneous interior value, while the diffusivity increases rapidly. Deeper layers are practically homogeneous. Lettau emphasizes that these results are very tentative since the data are from different sources, refer to different lunations, instruments used have different resolutions and accuracy, and there is a general lack of adequate detail concerning the phase lag determinations.

CURRENT WORK

The results of some work done in Research Projects Laboratory, MSFC, will now be presented briefly. Russell made an analysis based upon a homogeneous semi-infinite solid with the boundary temperature a specified, generally periodic, function of time [8]. The boundary temperature is based upon a curve calculated by Sinton from measured infrared data for surface radiation throughout a lunation [9]. The measurements were deliberately chosen by Sinton to allow ease in calculating a curve to fit the data.

Russell represented the boundary temperature by a trigonometric series. The solution was programmed for the IBM 7090 so that parametric studies could be made using different values for the thermal diffusivity. Figure 3 gives typical results of the study. The temperature is shown as a function of time at various depths beneath the surface for a particular value of thermal diffusivity ($\alpha = 10^{-5}$ cm^2/sec) throughout a lunation. The temperature variations are almost damped out at 20 centimeters below the surface; at this depth the temperature is constant at 229° K. This constant temperature is equivalent to the average temperature of the surface over one period and is the same for any value of the thermal diffusivity.

The Research Projects Laboratory, MSFC, has had a research contract with Arthur D. Little Company for about 2-1/2 years to study the thermal properties of non-metallic materials. This contract is supervised by Dr. Klaus Schocken, who has kept up with the literature in this area for about four years

TABLE III TENTATIVE DEPTH DEPENDENCE OF THE THERMAL PARAMETERS IN THE UPPER 10 cm OF THE LUNAR CRUST

DEPTH Z,cm	DIFFUSIVITY cm^2/sec	VOL. HEAT CAPACITY $joules/cm^3\ {}^\circ K$	a/ao
0	5×10^{-5}	1.34	1.00
1	2.5×10^{-4}	1.84	0.48
2	7.0×10^{-4}	2.09	0.38
3	1.35×10^{-3}	2.22	0.35
4	2.25	2.30	0.33
5	3.35	2.30	0.32
6	4.20	2.34	0.31
7	4.70	2.34	0.30
8	5.05	2.34	0.30
9	5.25	2.34	0.30
10	5.35	2.34	0.30
	5.40×10^{-3}	2.34	0.29

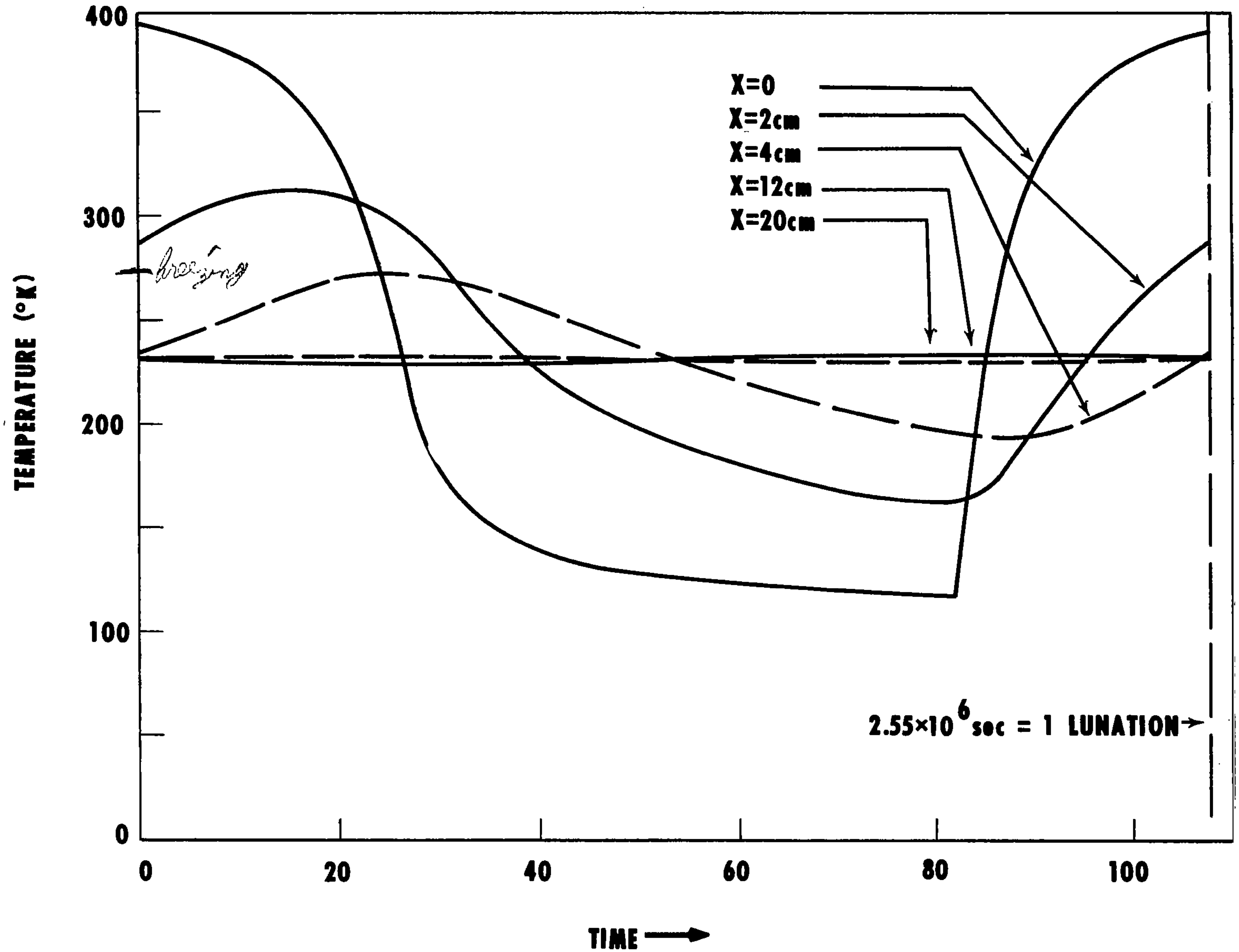

FIGURE 3. TEMPERATURE VERSUS TIME LUNAR SURFACE AND SUBSURFACE
($\alpha = 10^{-5}$ cm ^{2}/ sec)

[10, 11, 12, 13]. Table IV shows some values of thermal conductivity measured by A. D. Little for different terrestrial materials. The values for thermal inertia and diffusivity were computed from the measurements. The value for 70 micron size olivine compares more closely than the other materials to those deduced from lunar radiation measurements.

If one could determine the effective lunar thermal diffusivity and the effective thermal admittance with instrumentation on the moon, one could determine the effective thermal conductivity and volumetric heat capacity from the two measurements. The information gained could be further compared with laboratory measurements.

This is not an exhaustive survey of the work in this area, and there are a number of additional considerations that need to be taken into account. Among these are the possibility of internal heat generation due to radioactive decay, the peculiar directional radiative properties of the surface, non-homogeneity and non-constant thermal properties of the lunar material.

TABLE IV LABORATORY MEASUREMENTS OF THERMAL PROPERTIES

MATERIAL	DENSITY ρ kg/m^3	SPECIFIC HEAT C JOULES/kg°k	THERMAL CONDUCTIVITY WATTS/m°k	$[K\rho c]^{-1/2}$ m^{2}sec $^{1/2}$°k JOULE	α cm^2/sec
POWDERS					
PERLITE, 200μ	80	879	2.30×10^{-3}	7.17×10^{-2}	3.3×10^{-4}
COLLOIDAL SILICA, 200°A	64	879	3.72×10^{-3}	6.93×10^{-2}	6.6×10^{-4}
OLIVINE, 70μ	2000	795	1.26×10^{-3}	2.25×10^{-2}	7.9×10^{-6}
POROUS ROCKS					
PUMICITE	1270	920	6.02×10^{-2}	3.82×10^{-3}	5.2×10^{-4}
BASALT LAVA	2080	837	2.20×10^{-1}	1.63×10^{-3}	1.3×10^{-3}
SINTERED PERLITE	310	879	2.47×10^{-1}	1.22×10^{-2}	9.1×10^{-4}

NOTE: Above measurements taken from Ref. (7) and are for pressures below 10^{-4} mm Hg between temperatures of 77 to 370°K. Computations for α were done by Russell.

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AUTHOR'S NOTE

Since this paper was written, a Russian article [1] has come to the author's attention; it presents some evidence based upon lunar radio emission that the value for thermal inertia in 0.35 times the value derived by Wesselink and that the value of thermal conductivity is almost 50 times the previously accepted value corresponding to dust in a vacuum. Using this work as a basis, another Russian article [2] appeared which presented recalculated temperatures over the lunar surface as a function of phase. This latter work also uses a larger value for the solar constant and an emissivity for the surface equal to 0.9. The authors concluded from this that "the upper layer of lunar material does not consist of dust, but is a solid, porous material, perhaps somewhat pulverized." However, it was assumed that the upper layer of the moon has a constant density, which is then determined from radio emission measurements. They have assumed a homogeneous crust to a depth of about one meter and the radio emission data is "averaged" over the entire lunar disk.

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INFRARED METHODS OF MEASURING THE MOON'S TEMPERATURE

By

Charles D. Cochran *

One means of studying the surface temperatures of the moon is through measurements made in the infrared spectrum of the radiation emitted from the lunar surface. Although infrared techniques have inherent difficulties which limit the accuracy of the results, until man reaches the moon or gets above the earth's atmosphere, he must depend upon, and continually strive to improve, these and other limited earthbound techniques. Some of the methods used and difficulties encountered by the thermal investigators are presented in this paper.

The first infrared lunar temperature measurements were taken by the Earl of Rosse in 1868 using a thermopile [1], with which he obtained a maximum temperature of 397°K. S. P. Langley and F. W. Very obtained similar results using the same type of instrument. The first significant measurements of lunar thermal radiation were begun in 1923 by Edison Pettit and Seth B. Nicholson. Using a vacuum thermocouple on the 100-inch Mount Wilson telescope, they obtained an average maximum temperature of 407°K and a minimum of 120°K. William N. Sinton in 1958 started his work on isothermal contouring of the lunar surface and obtained a low temperature reading of 120°K, as did Pettit and Nicholson. Sinton used a Golay cell detector on the 42-inch Lowell Observatory telescope.

The most recent measurements on the thermal emission from the surface of the moon have been performed by R. W. Shorthill and J. M. Saari of the Boeing Scientific Research Laboratory and by Bruce C. Murray of the California Institute of Technology.

During the March 1960 eclipse Shorthill and associates made thermal measurements of the moon with a thermistor bolometer detector at the 72-inch Dominion Astrophysical Observatory [2]. The telescope was driven to scan the rayed craters Tycho, Aristarchus, and Copernicus during totality. These craters proved to be at a higher temperature than their surroundings. Thus Shorthill and associates are credited with discovering the temperature anomalies on the moon. During the September 1960 ecplise Shorthill used his thermistor bolometer on the 60-inch Mount Wilson Observatory [3]. Again he found that Tycho,

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Aristarchus, and Copernicus cooled less rapidly than the surrounding lunar surface; Kepler also exhibited these properties. On the night following the eclipse these craters were found to be cooler than their surroundings.

Murray of California Institute of Technology made thermal measurements of the non-illuminated portions of the moon during August and September 1962, using a mercury-doped germanium detector on a portable 20-inch telescope at White Mountain, California [4]. He confirmed the temperature anomalies which Shorthill had discovered. Murray also found that the temperature anomaly craters cooled less rapidly during lunation as well as during an eclipse, although the anomalies are more pronounced during an eclipse. In addition to these rayed craters, Murray found about 30 other suspected temperature anomaly craters. While searching for these anomalies, Murray detected a new low temperature of 105°K, the lowest temperature that his radiometer could read due to background limitations. Figure 1 is an example of a trace recording that shows a temperature anomaly at A on the trace and a low reading of 105°K. Murray found that after Tycho had been in the lunar night for about 12 days its temperature dropped to the background limit of 105°K. He believes the moon's minimum temperature is below the background limit, especially at higher selenographic latitudes and near the morning terminator.

There are many obstacles which stand in the way of lunar temperature measurements. The major hindrance is the absorption of the earth's atmosphere. The earth's atmosphere acts as a filter in that it absorbs and re-radiates radiation incident upon it, particularly in the infrared, and, in addition, it scatters the radiation. As one observes an object in the infrared region of 10.5 to 12.5 microns for different zenith angles (other than the vertical), the transmission is reduced even more (Fig. 2). Fortunately there are regions in the infrared spectrum which transmit a large portion of the energy. These regions of transmission are called windows [5] and are shown in Figure 3. Both the width and percent transmission of these windows are dependent on pressure broadening and the amount of water vapor or gases present. The percent transmission increases with higher altitudes, where there is less water vapor, air mass, and pressure. Both the long and short term changes of transmission affect the accuracy of temperature measurements.

Pettit and Nicholson measured an averaged maximum sub-solar temperature of the moon of 407°K [6], and Murray measured a minimum of 105°K near the morning terminator. The Planck blackbody energy distribution for the measured values is shown in Figure 4. The wavelength at which the maximum amount of energy occurs for these two temperatures is shown by the Wien's displacement curve in Figure 5. The peak for the maximum lunar temperature of

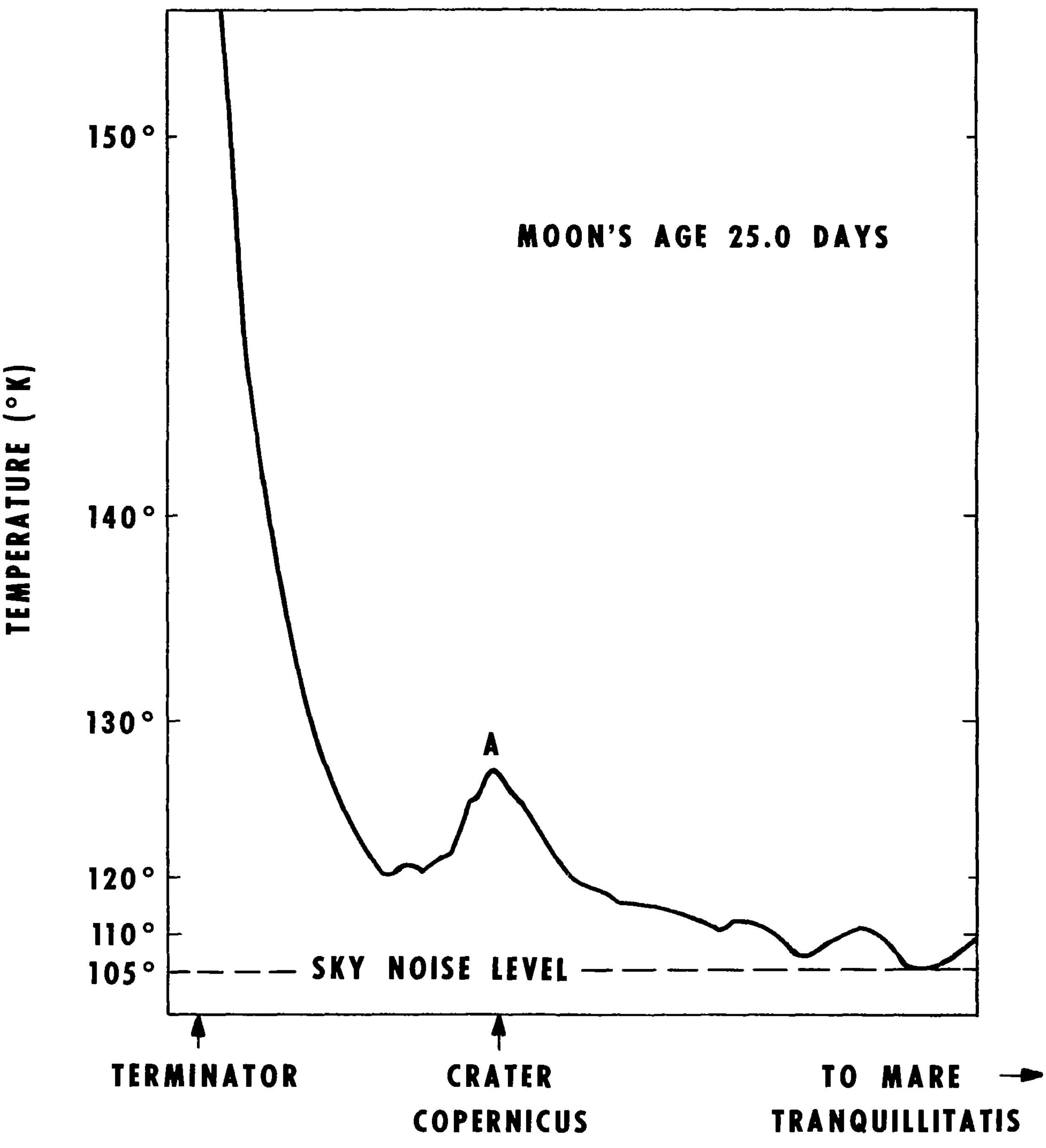

FIGURE 1. TEMPERATURE RECORDING ACROSS THE ANOMALOUS CRATER COPERNICUS

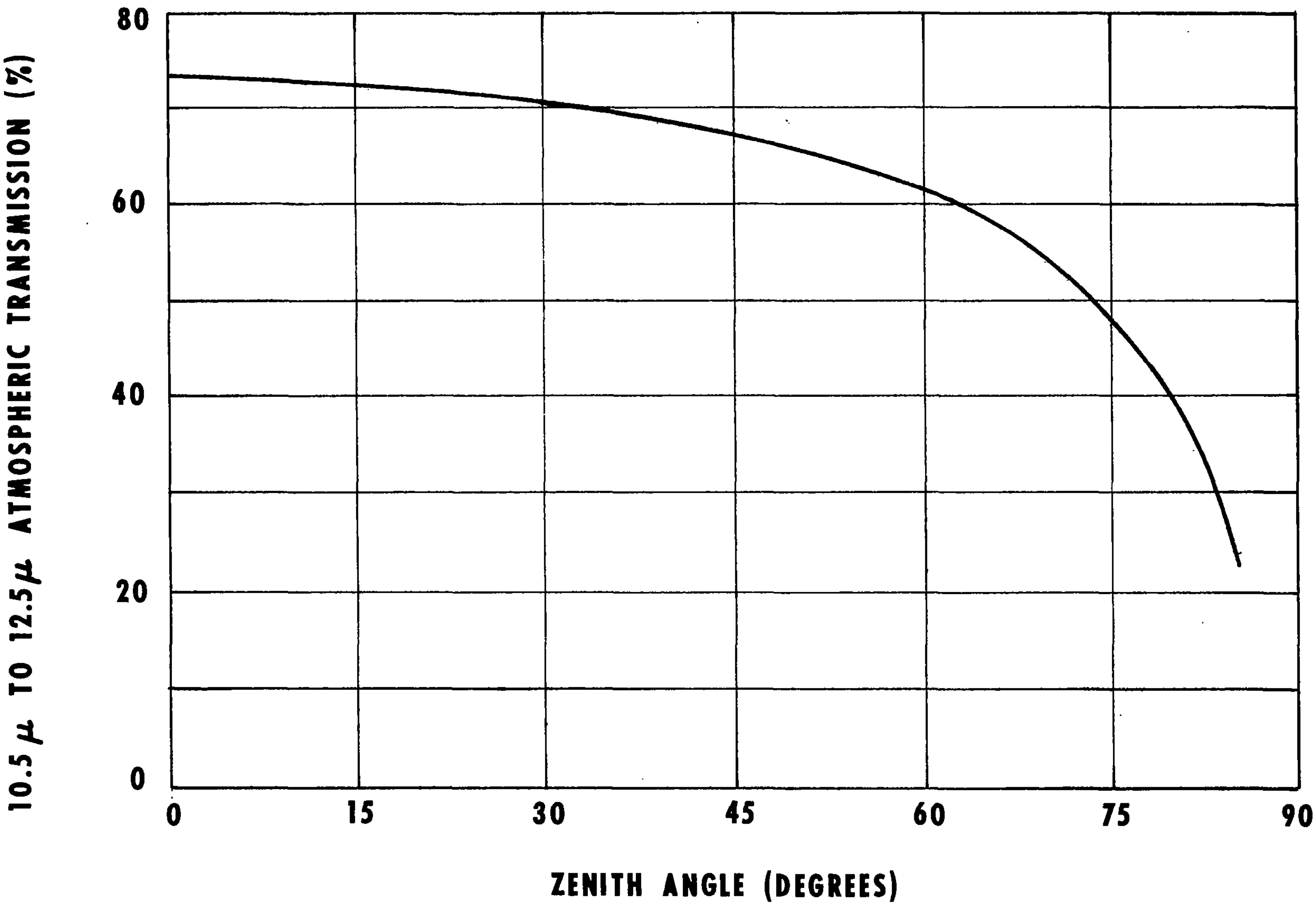

FIGURE 2. ATMOSPHERIC TRANSMISSION VERSUS ZENITH ANGLE

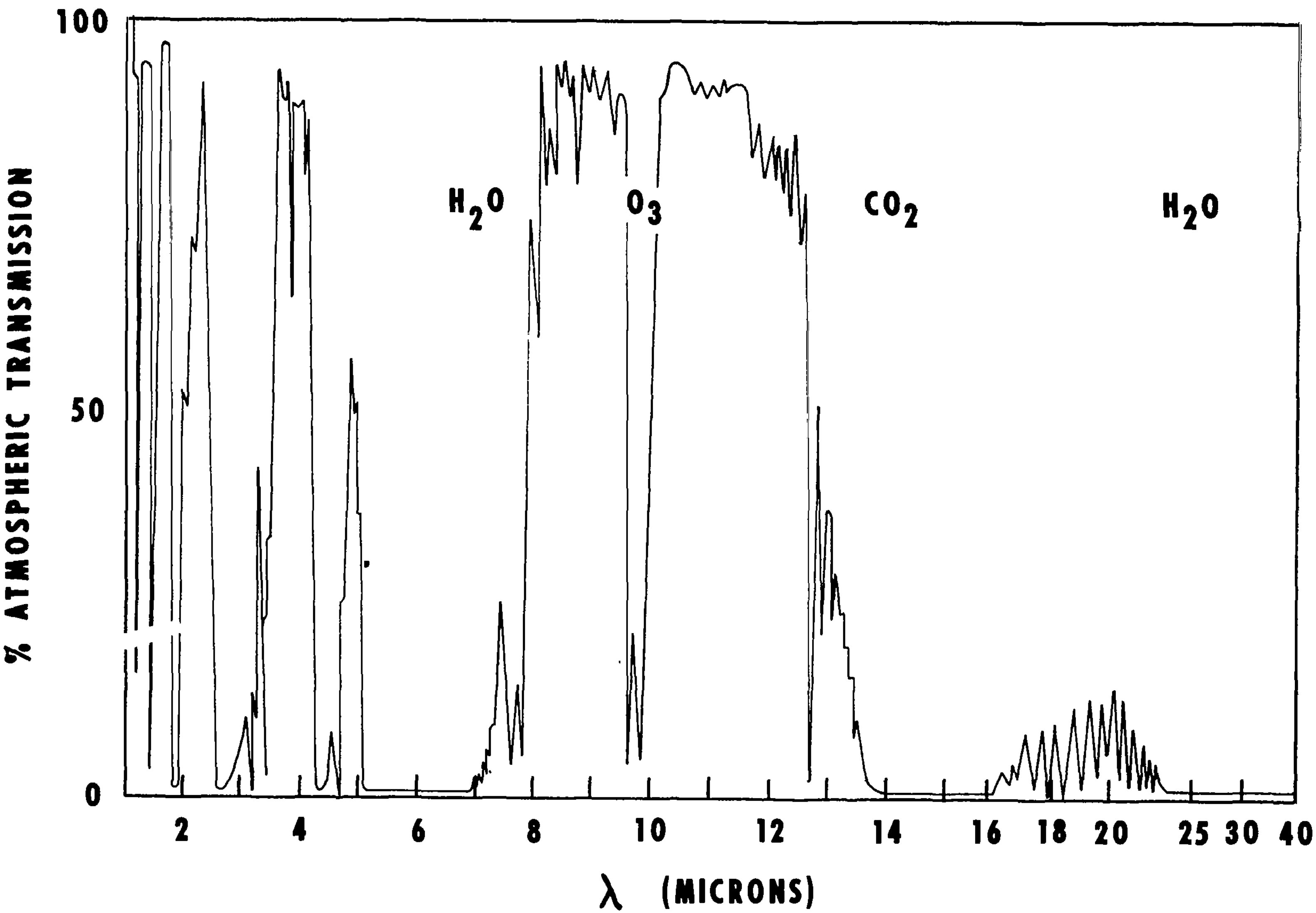

FIGURE 3. ATMOSPHERIC TRANSMISSION

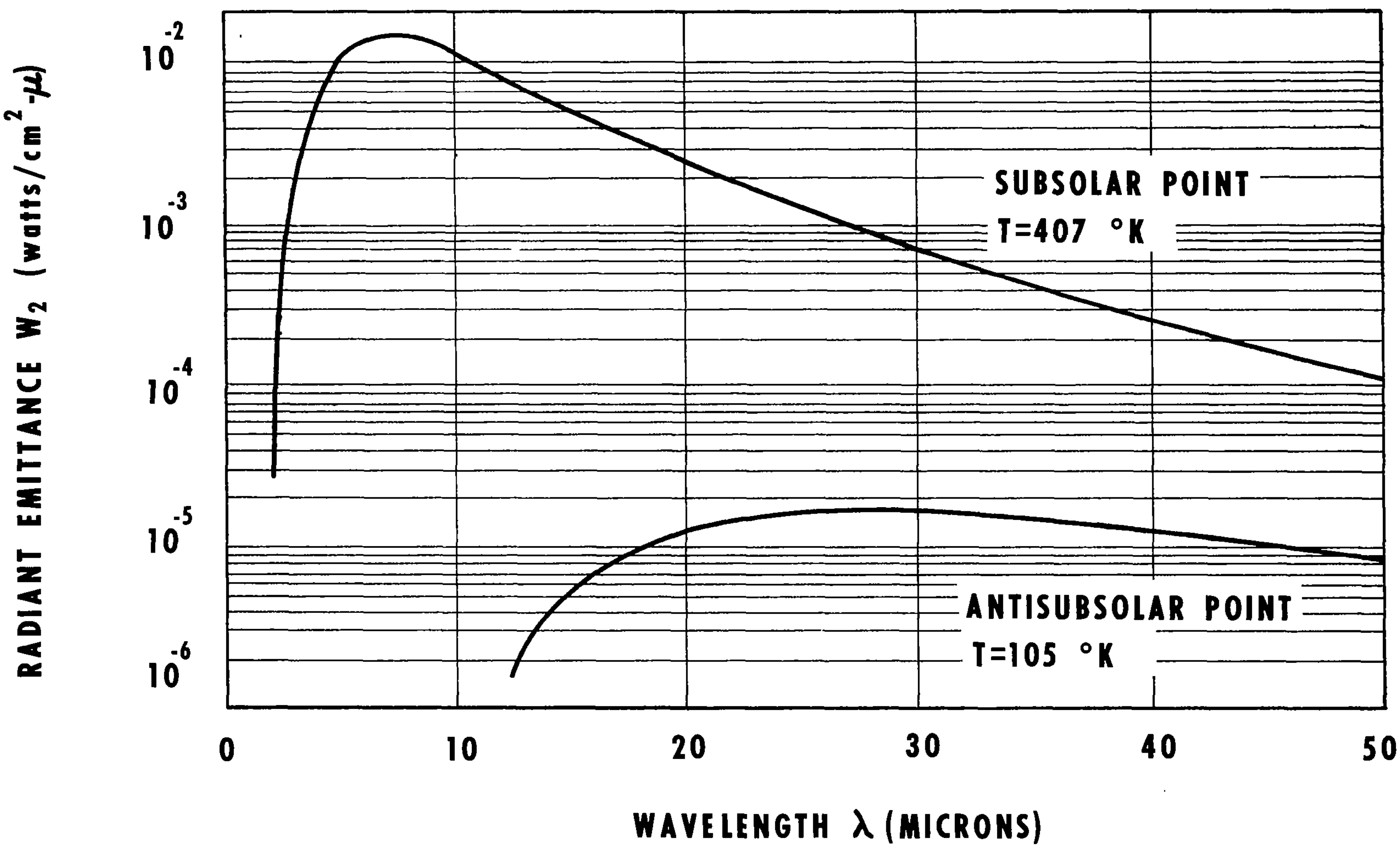

FIGURE 4. PLANCK DISTRIBUTION OF MEASURED LUNAR TEMPERATURES

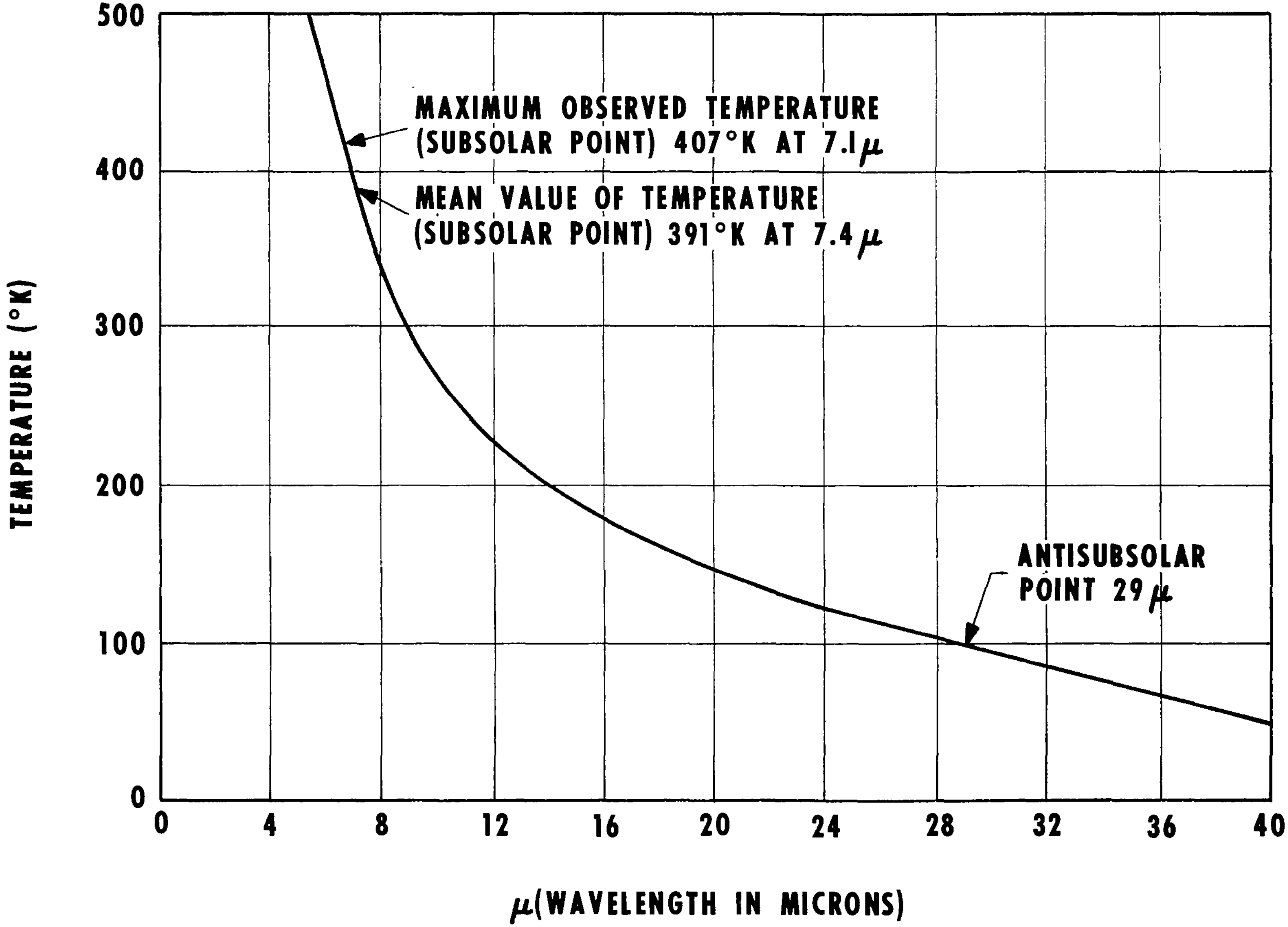

FIGURE 5. WIEN'S DISPLACEMENT

407°K occurs at 7.1 microns, and the minimum temperature peaks at 29 microns; this calls for a detector that will respond at these wavelengths. Looking at a group of detector parameters in Figure 6, there are several that seem desirable [7]. The mercury-doped germanium detector meets the requirements of the sub-solar temperature, and the Ge: Zn-I meets the requirements of the anti-sub-solar point. The immersed thermistor meets the wavelength requirements of both temperatures, but the normalized detectivity (D^*) is not as attractive. Referring to the atmospheric transmission in Figure 3, we see that the use of the Ge: Zn-I for 29 microns is not desirable because of the poor transmission window, but there is a good window for the mercury-doped germanium at the 8-13 micron region. This limits the selection to the thermistor bolometer and the mercury-doped germanium detector that were used by Shorthill and Murray respectively. When these are contrasted against each other on the basis of the same size telescope (24-inch is used here), we see from Figure 7 that the mercury-doped germanium detector is about 100 times more sensitive on the full moon at the sub-solar point. This graph also shows that as one scans from the sub-solar point to the limb, the minimum detected temperature becomes higher. The resolution changes from a circle at the center of the moon to an ellipse near the limb.

Shorthill has changed his radiometer to use the more sensitive mercury-doped germanium detector [8]. Even though Shorthill used a thermistor bolometer detector, he used a 72-inch and a 60-inch telescope at the Newtonian focus; Murray used a 20-inch portable telescope at the Cassegrainian focus. The Newtonian focus gave Shorthill more available energy to be focused on the detector and the larger telescope gave smaller resolution. The larger the telescope used, the better spatial thermal resolution one can get for the same focal ratio of the detection system. The resolution falls off as one moves further into the infrared spectrum as illustrated in Figure 8. Shorthill used 10 seconds (19 km) of arc on the lunar surface, and Murray used 17 seconds (33 km) of arc.

To make a thorough thermal map of the moon and to ensure that anomalous or interesting features can be detected, the moon should be scanned in a raster pattern as shown in Figure 9. There are two logical methods for scanning the moon: first by the use of a focal plane scanner in the X and Y directions on the telescope, and, second, by the use of the earth's rotation and moon's change in declination. In the second method the day of the month or year determines the rate of change in the moon's declination (Fig. 10) and this in turn determines the spacing or overlapping of succeeding scans. It takes approximately two minutes to scan the maximum diameter of the lunar disc at the rate of the earth's rotation and the motion of the moon in its orbit. Due to the moon having a non-circular orbit, its rate of change in right ascension varies, which alters slightly the two-minute period required to scan the maximum diameter of the moon. This is

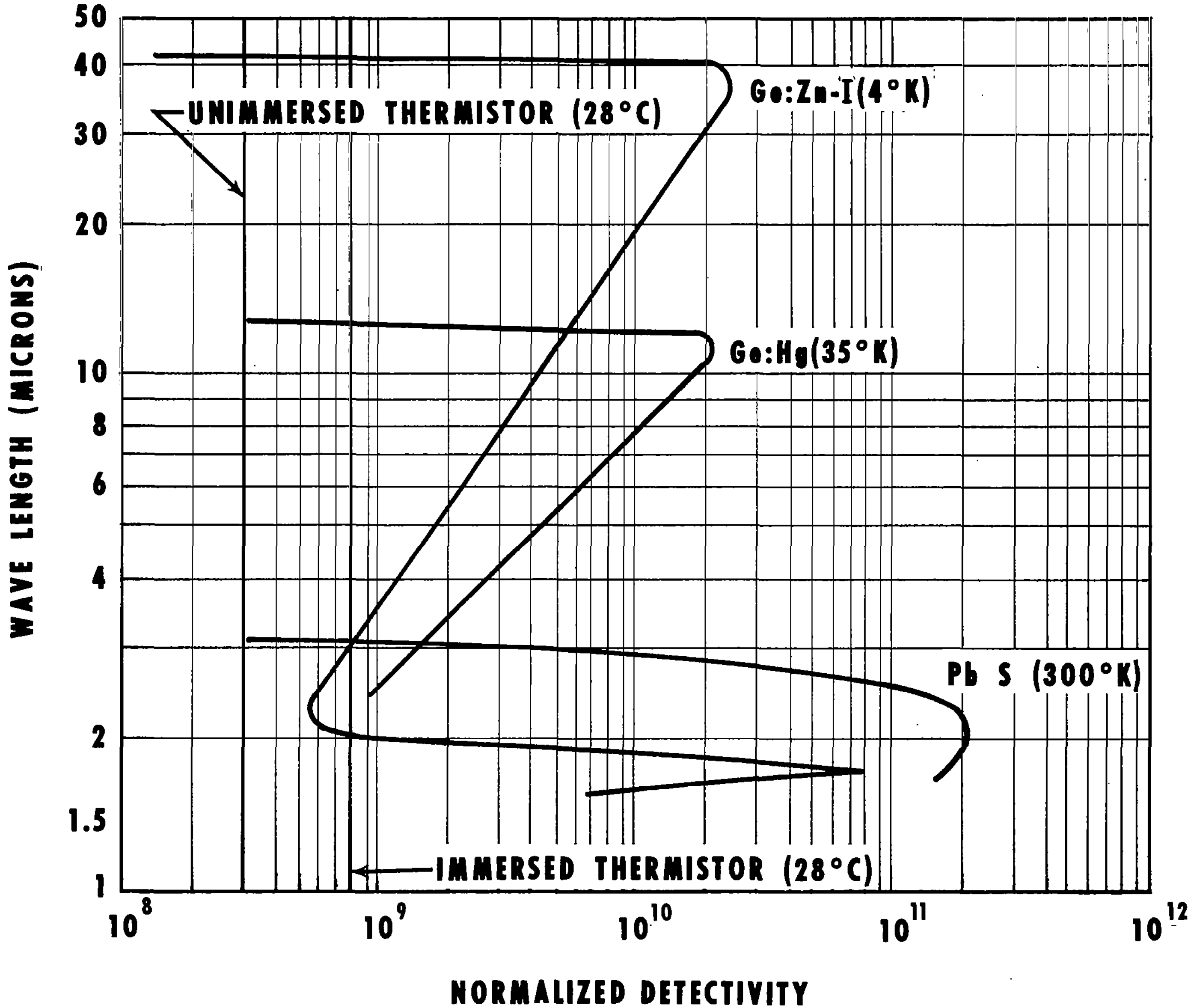

FIGURE 6. DETECTIVITY VERSUS WAVELENGTH

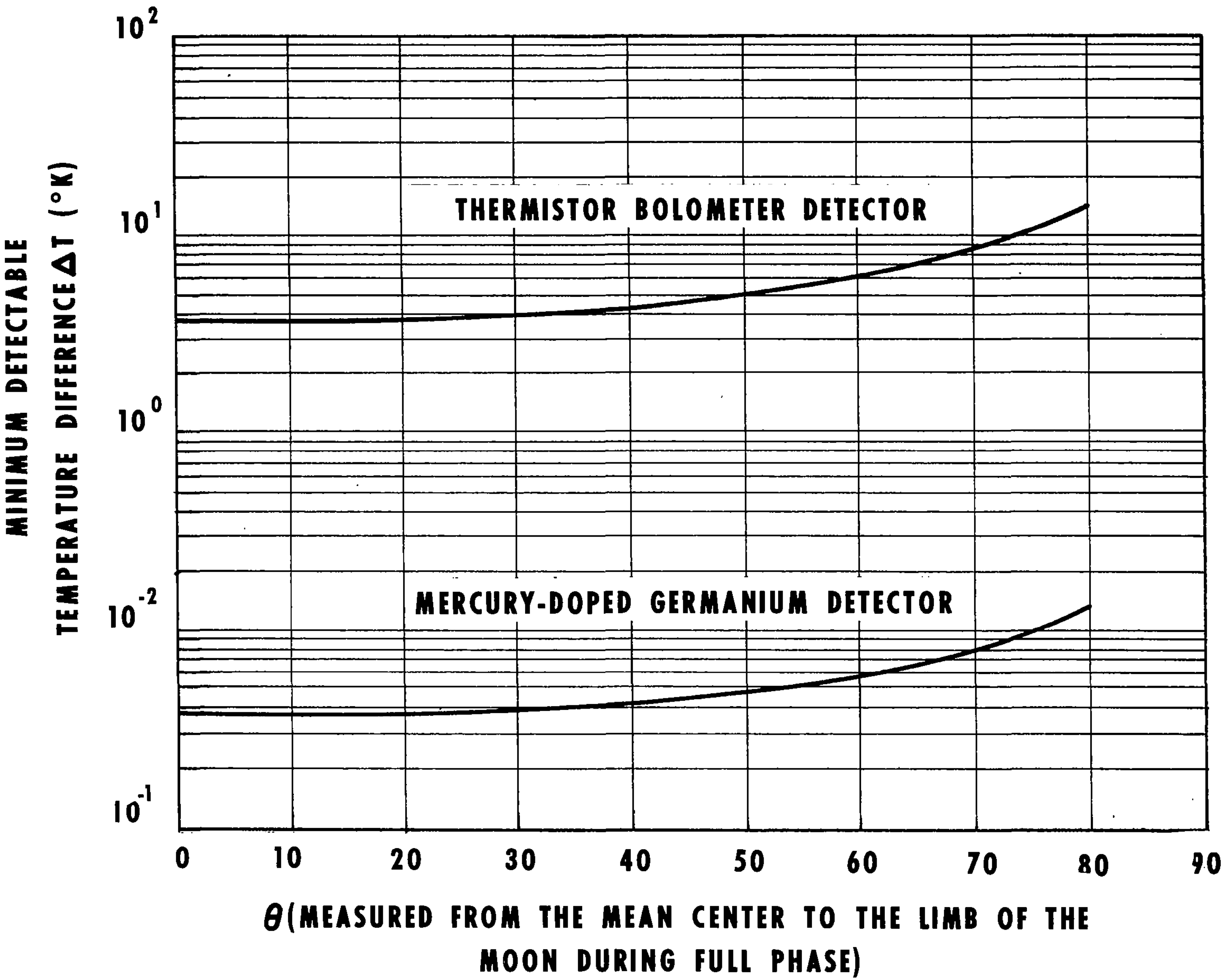

FIGURE 7. MINIMUM DETECTABLE TEMPERATURE DIFFERENCE VERSUS θ

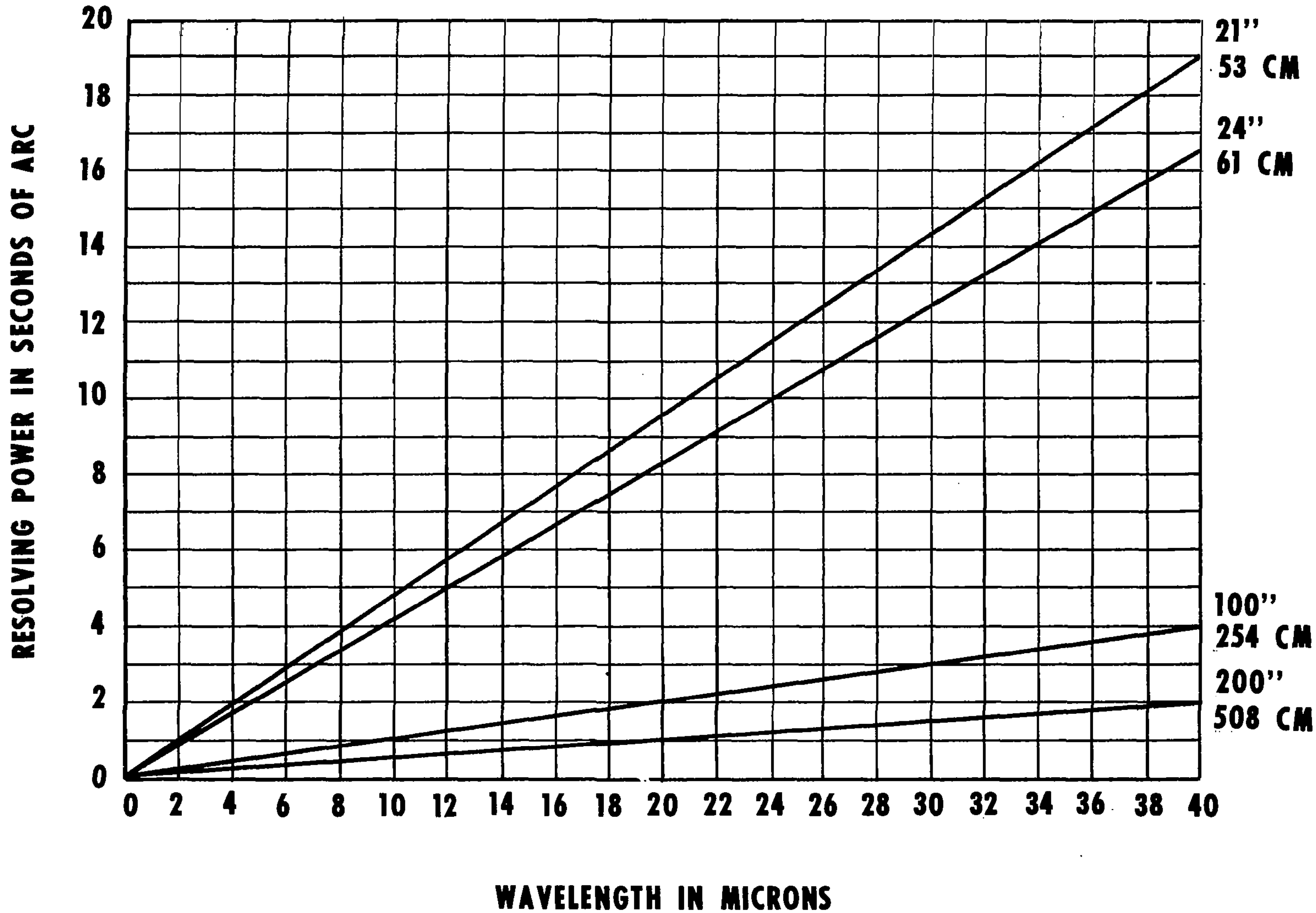

FIGURE 8. RESOLVING POWER VERSUS WAVELENGTH

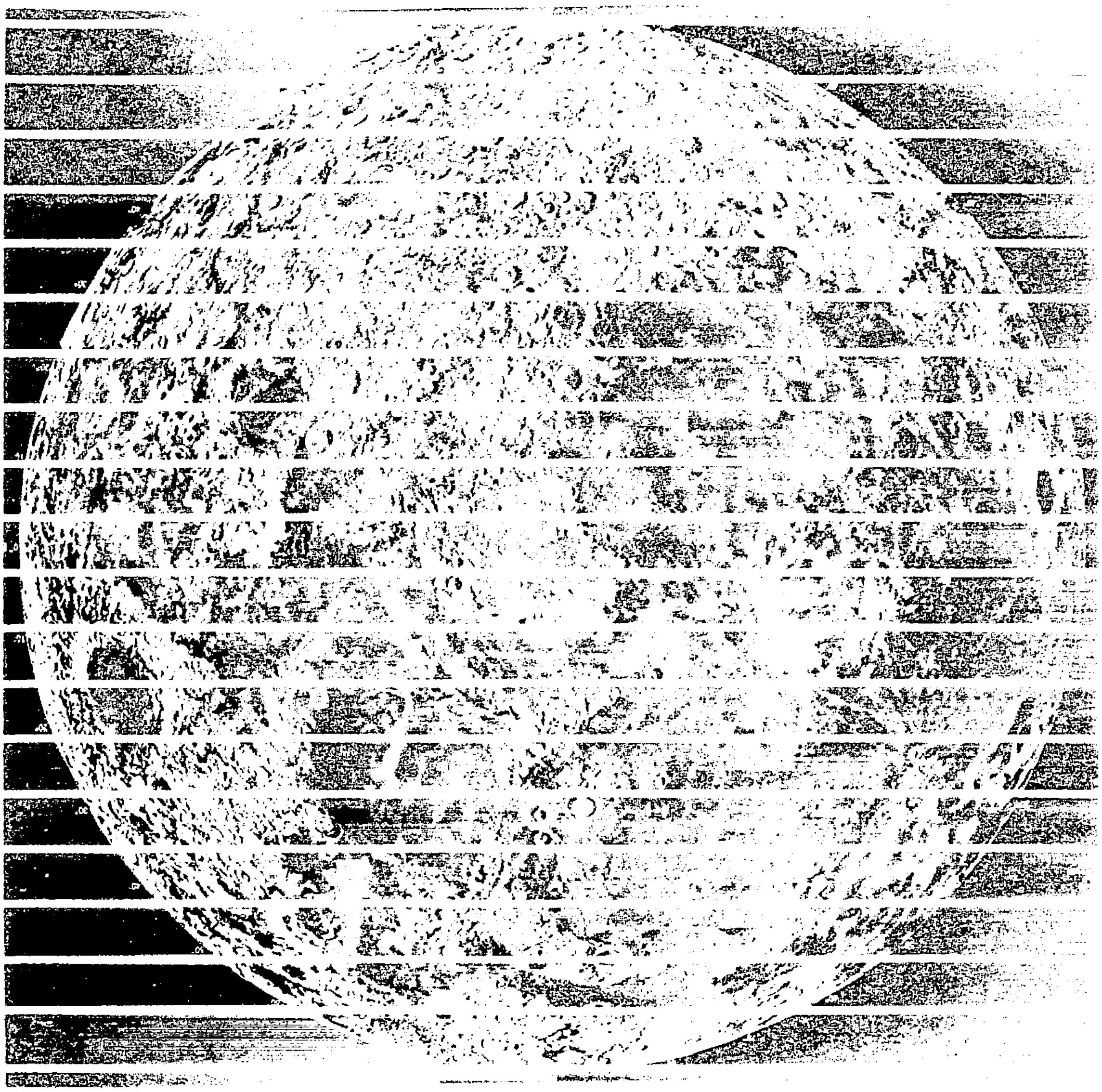

FIGURE 9. RASTER SCAN PATTERN FOR THERMAL MEASUREMENTS

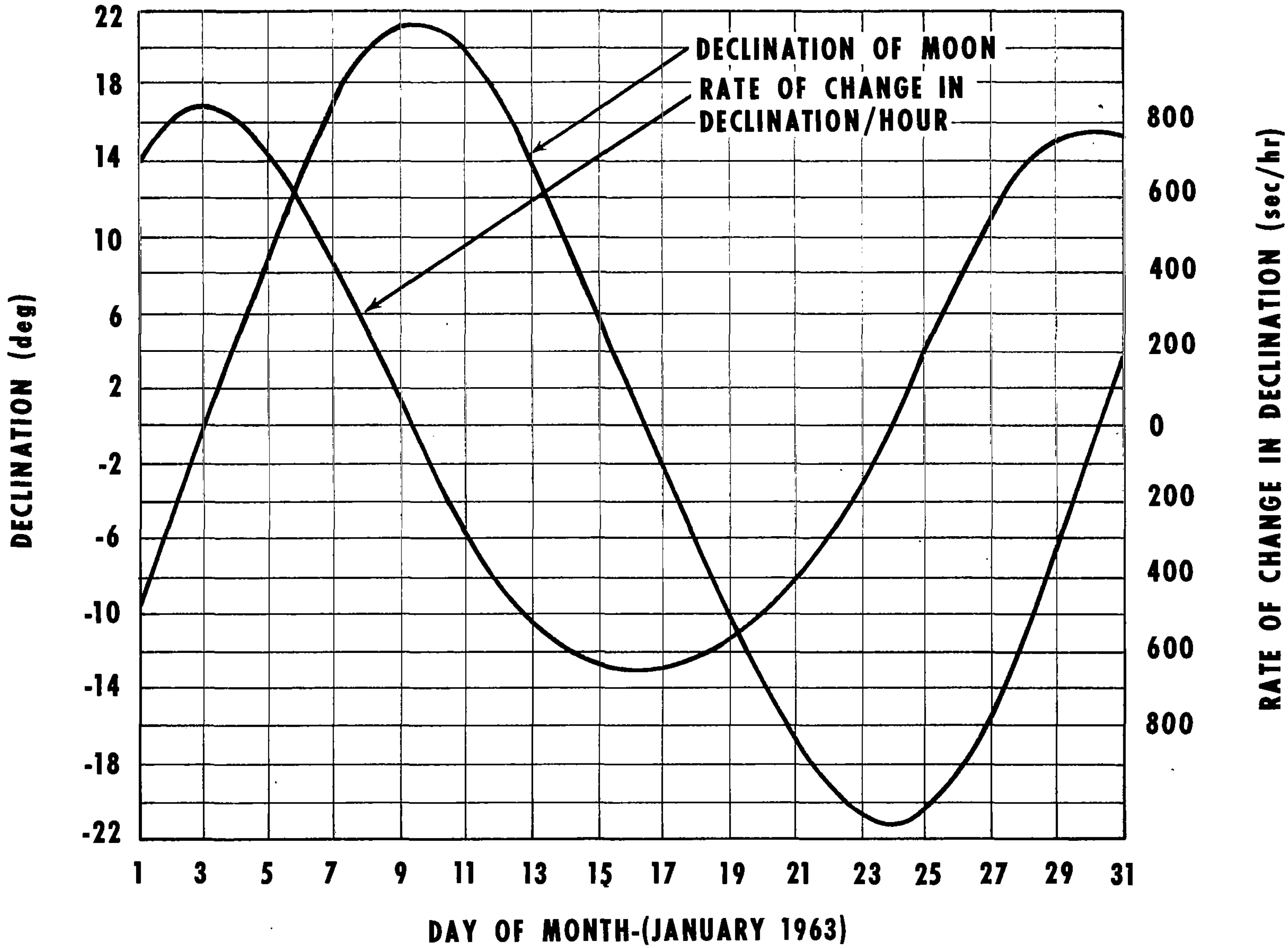

FIGURE 10. DECLINATION VERSUS DAYS OF MONTH

shown in Figure 11 which also illustrates the rate of change in declination per two-minute period. The rate of change in declination offers a unique method to scan the moon, but in turn its non-uniform rate of change presents difficulties in that it would cause unequal spacing of the scans. This is further complicated by the geocentric and physical librations of the moon which result in the presentation of a different portion of the moon from night to night [9]. This is shown in Figure 12. These uncertainties complicate the correlation of temperature measurements to their physical position on the moon.

The correlation of temperatures to positions on the moon has not been accurately performed in the past. The author and James A. Fountain of the Research Projects Laboratory of Marshall Space Flight Center have devised and used a promising technique to correlate measurements to positions. Figures 13, 14, and 15 show the photometer apertures on segments of the lunar surface and the corresponding photometric traces. As the photometer scanned the lunar surface, the defining aperture was photographed thus creating a black "spot" on the photograph. The scan path is on a line through these black "spots." The recorder trace is placed below the scan line for illustrative purposes in Figures 13, 14, 15. The traces were measured in the yellow, blue, and ultraviolet respectively. This gives an absolute correlation of measurement to position on the moon. These photographs are preliminary.

Unique features of the radiometer are shown in Figure 16. In addition to the focal plane aperture, the radiometer uses a two-detector system which increases the signal strength to 1.4 times over that obtained by a single detector. This results because the signal increases by a factor of two and the noise increases only by a factor of the square root of two. The radiometer interior is cooled to liquid nitrogen temperature, thus eliminating much of the radiation from the radiometer itself. This radiometer can improve the thermal accuracy of present measurements and give accurate correlation of temperatures to positions. Even with the correlation method, errors can occur due to the shimmering of the lunar image caused by the atmosphere and different refraction of visible and infrared wavelengths (Fig. 17) [10], but these are small.

In order to understand the lunar environment better, considerable additional work remains to be performed. Below are listed a number of experiments which should be carried out. Some of these have already been planned by some investigators for the coming year.

1. Map small resolution (16 km or less) isotherms on both the illuminated and non-illuminated moon.

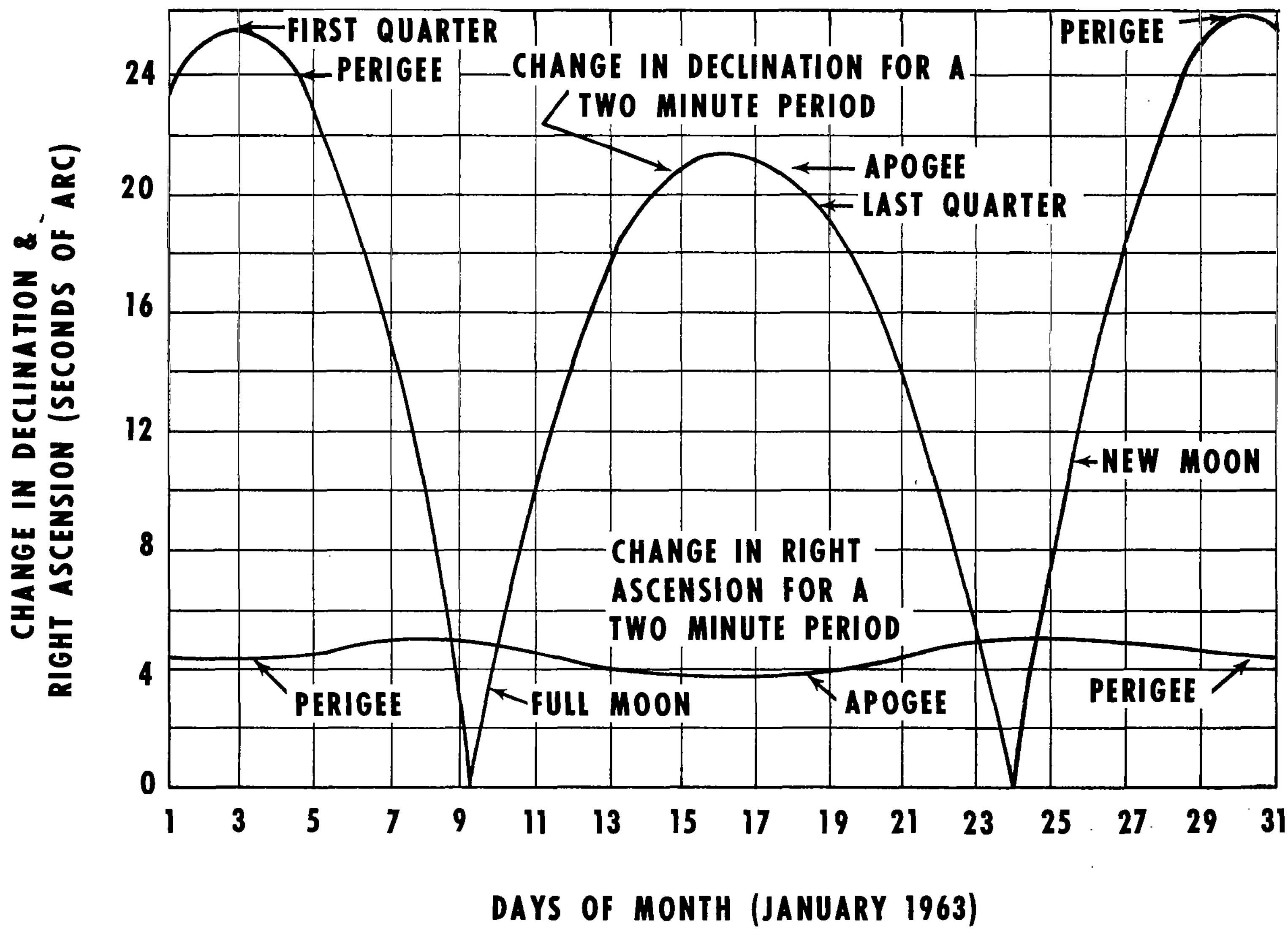

FIGURE 11. DECLINATION AND RIGHT ASCENSION VERSUS DAYS OF MONTH (JAN. 1963)

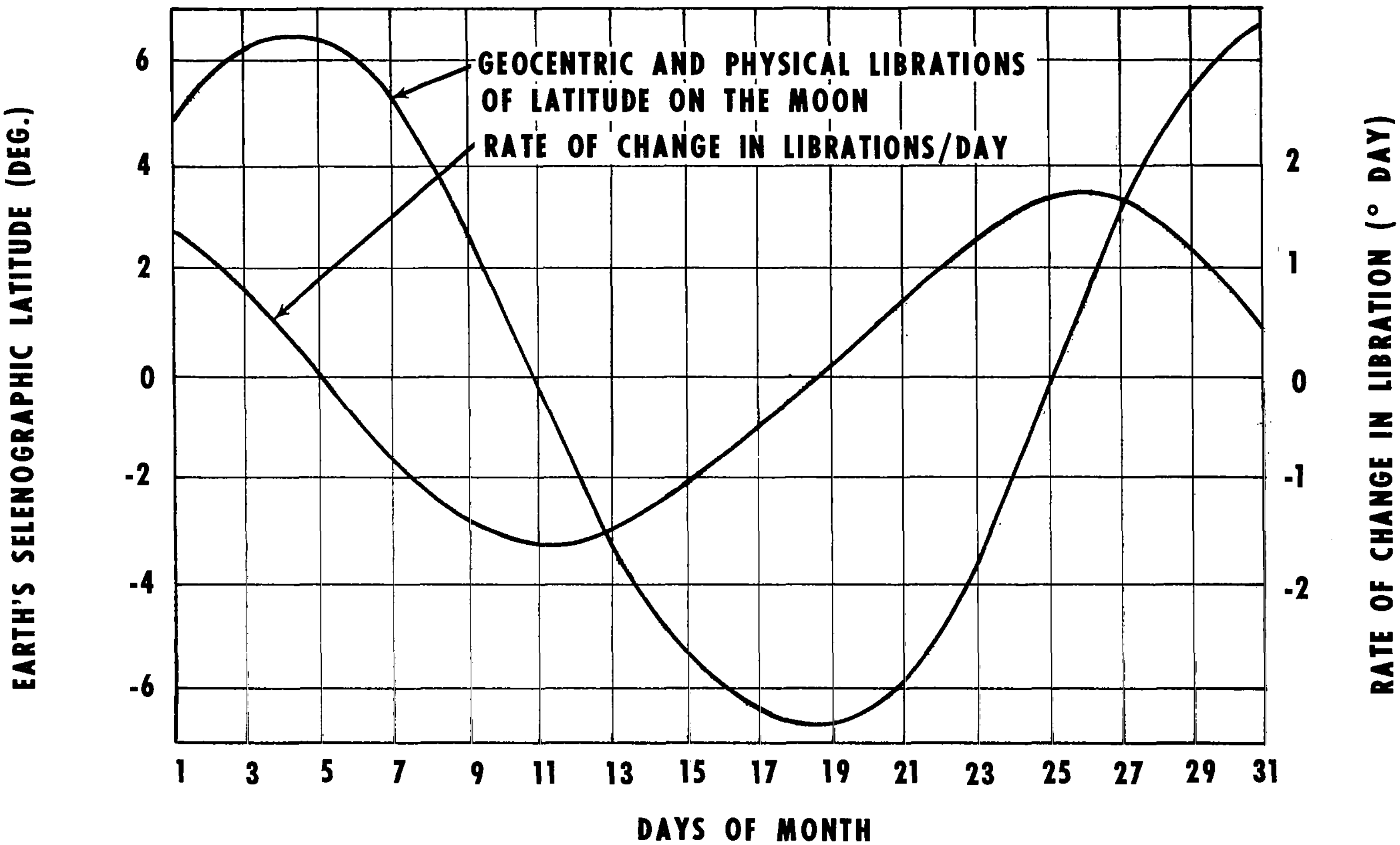

FIGURE 12. EARTH'S SELENOGRAPHIC LATITUDE VERSUS DAYS OF MONTH (JAN. 1963)

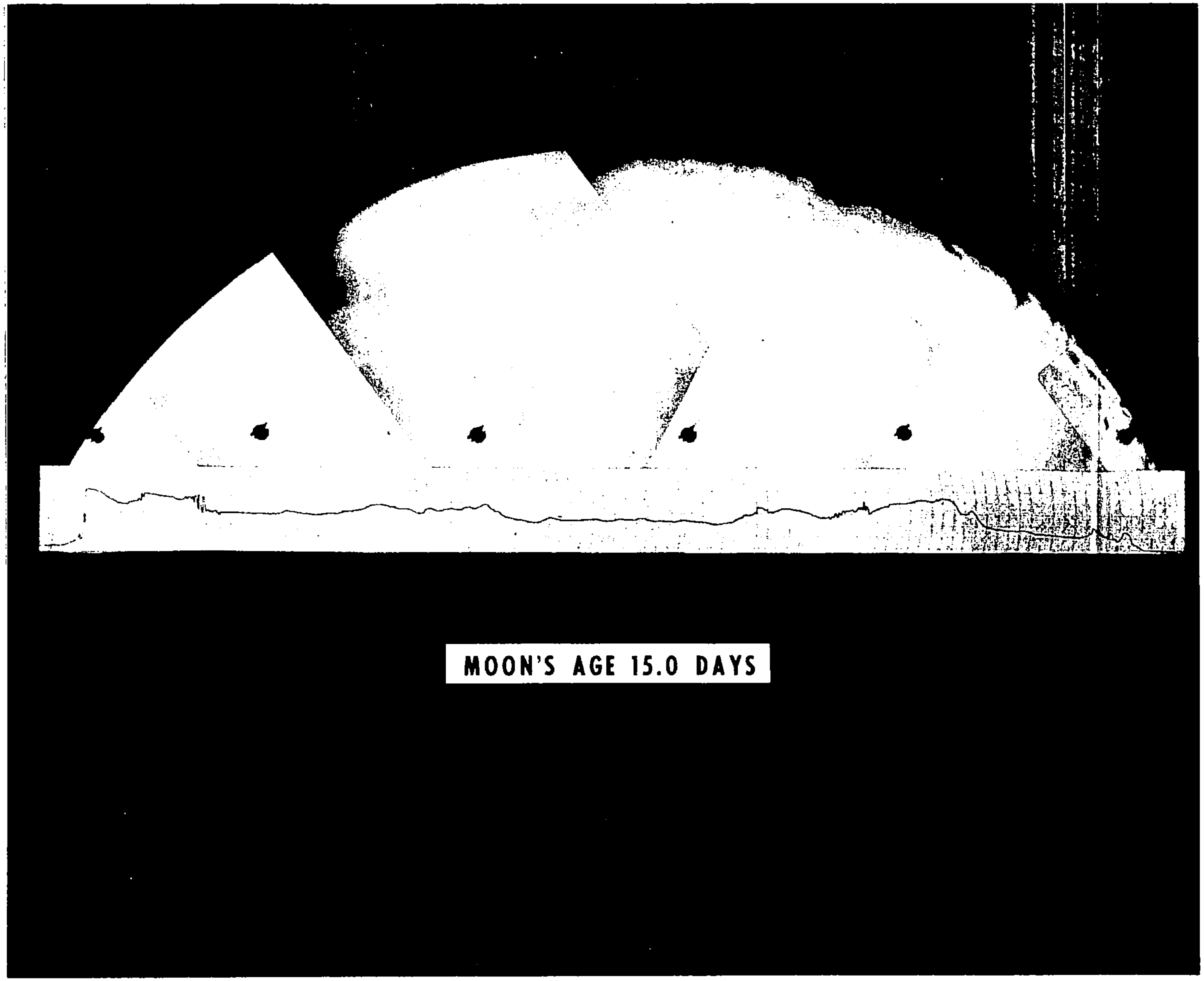

FIGURE 13. PHOTOMETRIC SCAN OF THE MOON IN YELLOW

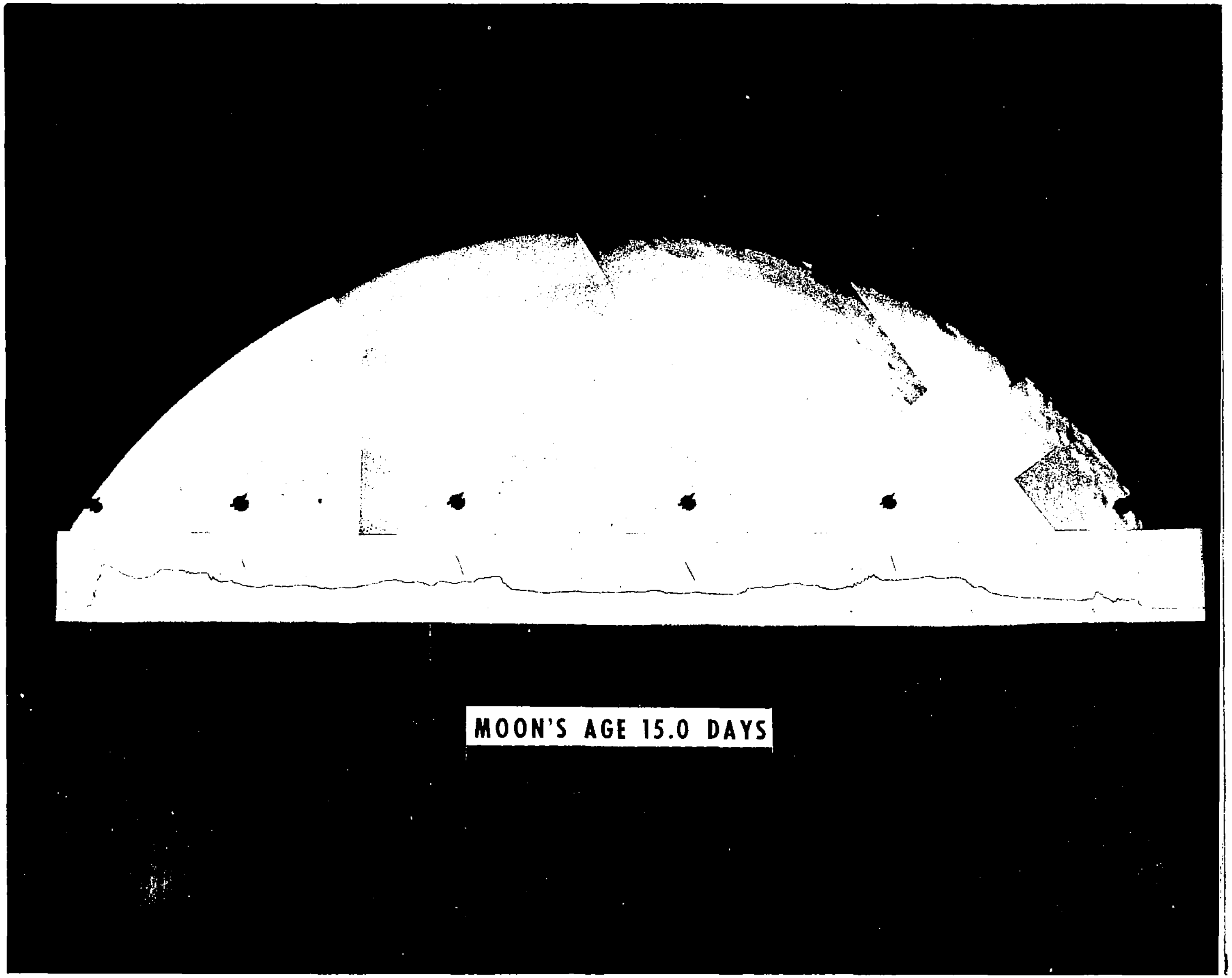

FIGURE 14. PHOTOMETRIC SCAN OF THE MOON IN BLUE

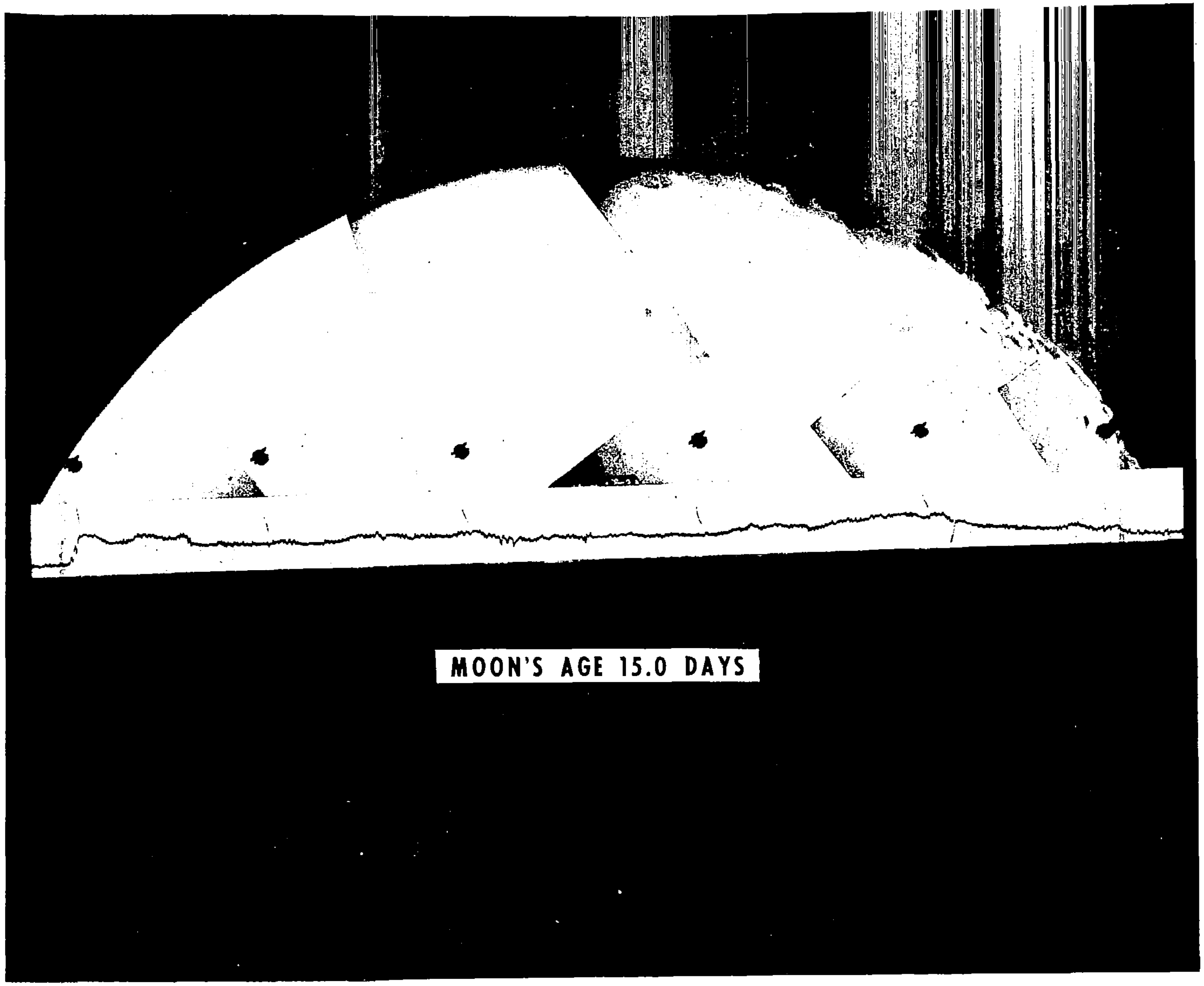

FIGURE 15. PHOTOMETRIC SCAN OF THE MOON IN NEAR ULTRA VIOLET

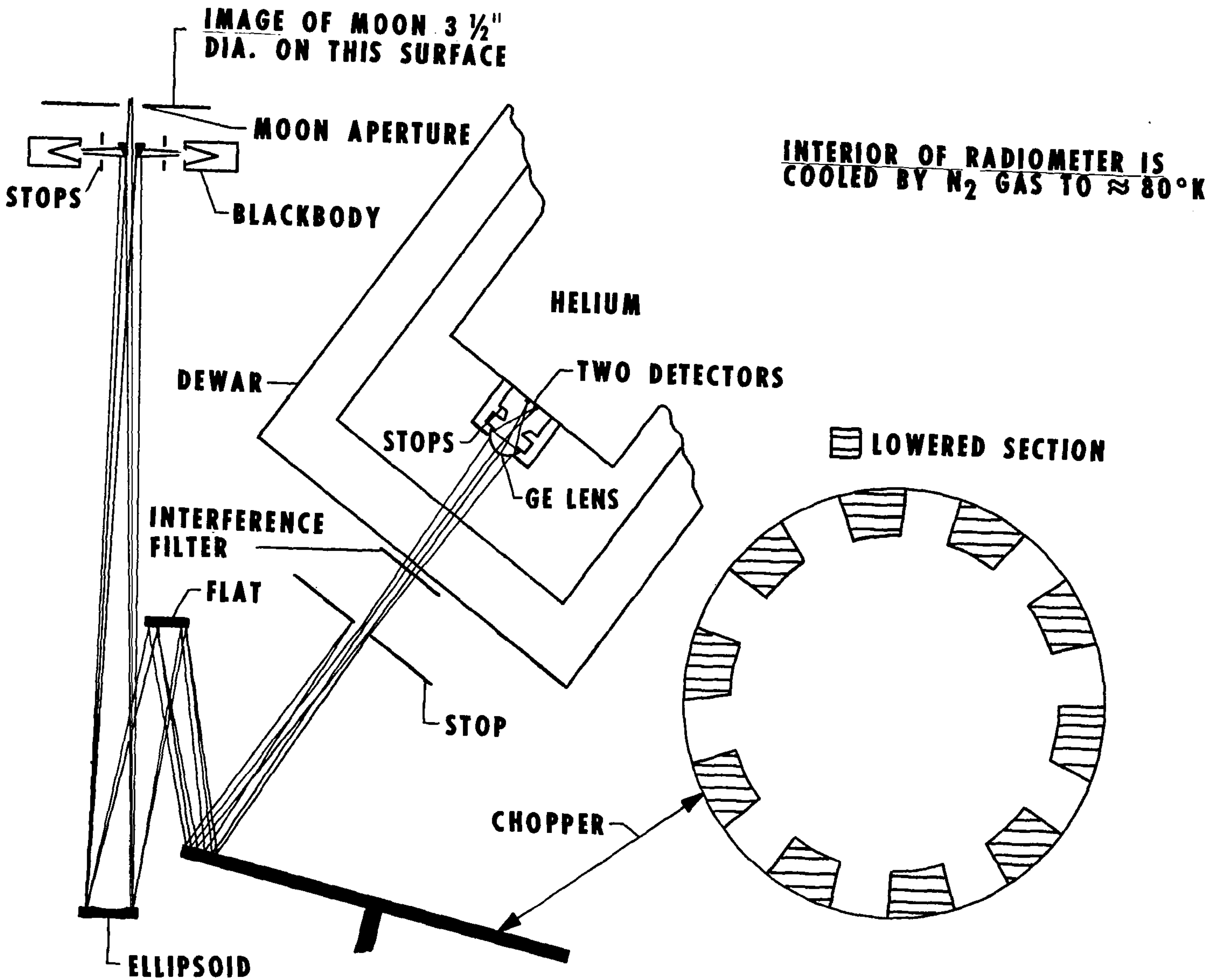

FIGURE 16. ELEMENTS OF THE RESEARCH PROJECTS LABORATORY RADIOMETER

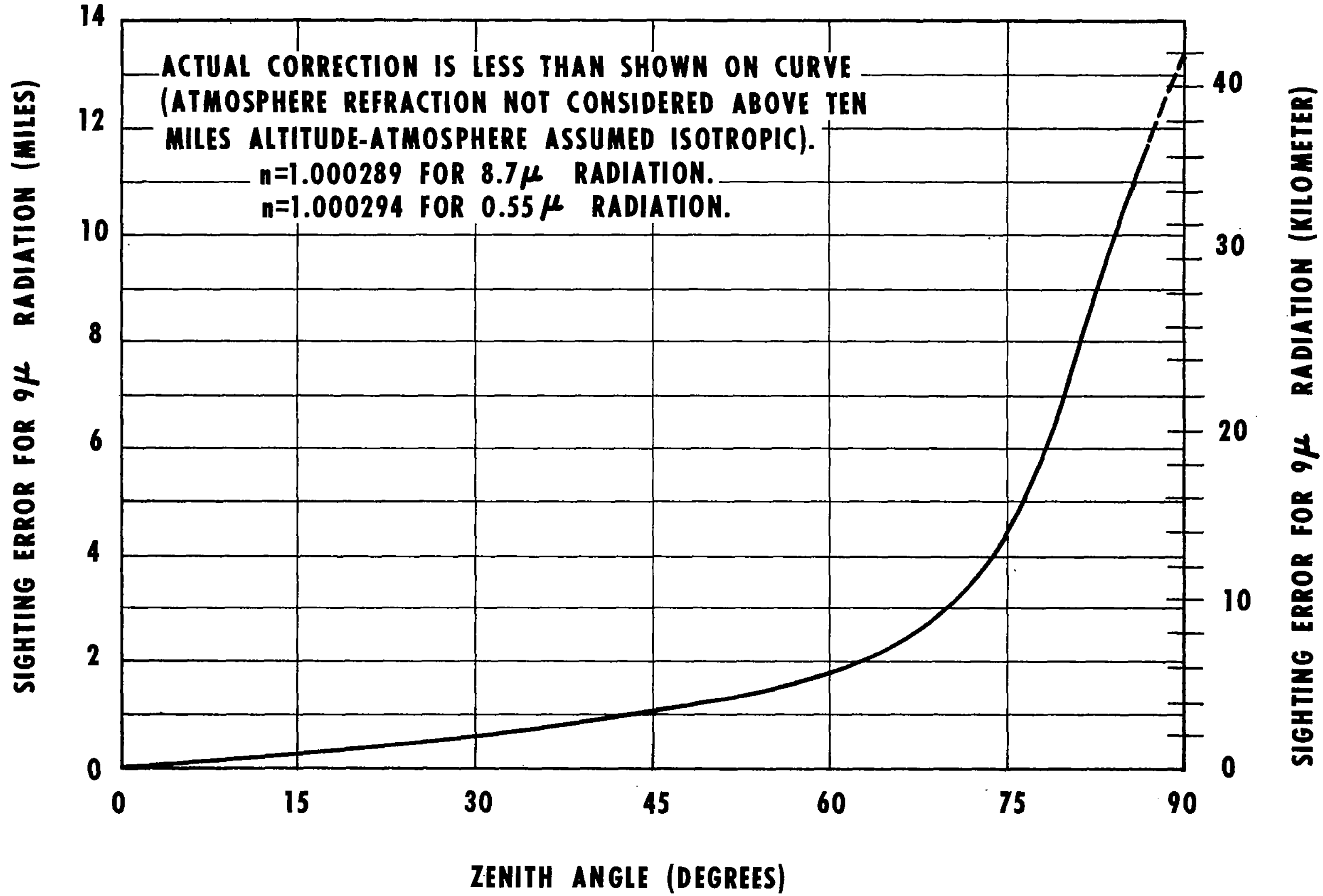

FIGURE 17. SIGHTING ERROR VERSUS ZENITH ANGLE

2. Make lunation measurements of particular areas of interest.

3. Make shadow temperature studies.

4. Look at crater slopes and bottoms of depressions for temperature differences during different phases and eclipses.

5. Make infrared emission studies simultaneously with radio measurements.

6. Make simultaneous measurements to correlate the photometric and polarization properties with the infrared properties.

7. Make more eclipse measurements.

8. Concentrate on the morning terminator for temperature anomalies rather than albedo anomalies.

In all of these experiments the temperatures should be accurately correlated to the actual location on the moon.

CONCLUSIONS

Valuable insight to understanding the nature of the lunar surface can be obtained with infrared and photometric measurements. These are characteristics of the moon that can be measured quantitatively and not postulated as are some characteristics of the moon. The previously mentioned experiments can be done on earth now to better design and prepare manned spacecraft and scientific payloads before they land on the moon.

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SECTION II

EXPLORATION OF THE MOON

Chapter 1

A LUNAR SCIENTIFIC MISSION

By

Daniel Payne Hale*

INTRODUCTION

In this paper an attempt will be made to indicate all of the major areas of lunar scientific studies and to outline briefly the formulation of a lunar scientific mission. The lunar exploration program may demand resources far in excess of those available for any mission likely to occur before the 1970's; furthermore much of the necessary instrumentation has yet to undergo even preliminary development. Accordingly, the mission suggested herein may be unrealistic; however, this does not mean that such ideas are without value. Indeed it can be only by a process of iterative projections of imagination, and of balancing objectives against resources, that man shall ever comprehend and achieve a sound, efficient lunar mission.

Mission Scientific Systems

First it is desirable to survey the known physical quantities and processes associated with the moon. This will be done by proceeding from phenomena which are relatively independent of the moon, to properties and processes which intimately characterize the lunar environment. Moreover one can start with single parameters and then proceed toward comprehending processes involving two or more parameters and their changes with time. Fundamental to all geophysical observations is knowledge of the time of the event; concurrent measurement of time will be assumed throughout.

It is logical to begin with extralunar phenomena which affect the moon; these are shown in Table I. The electromagnetic flux incident upon the moon is primarily solar in origin and is received directly from the sun during the lunar day and by reflection from the earth (so called earthshine) during the lunar night over approximately 60 percent of the lunar surface. Elementary particulate flux incident upon the moon also arises primarily from the sun although for certain energy regions contributions from sources outside the solar system are important. These particles are chiefly protons and alpha particles composing the solar wind;

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however there may be neutrons as well. Finally there are meteoric particles ranging upward from dust particles of probably micron diameter to huge bodies whose size, judging from the magnitude of what are assumed to be lunar impact craters, must be reckoned in kilometers. Events involving the impact of large meteoric bodies upon the lunar surface may be quite rare now but may have occurred much more frequently in the past. However, if the lunar meteoric flux is anywhere near that prevailing at the earth [1], the moon must acquire several hundred tons a day of meteoric particles whose individual masses are a fraction of a gram and lower. Assuming the moon to be approximately four billion years old, accumulations of meteoric material of the order of magnitude of meters are possible.

TABLE I. EXTRALUNAR PHYSICAL PHENOMENA AFFECTING THE MOON

INCIDENT ELECTROMAGNETIC FLUX		TERRESTRIAL SOLAR STELLAR
CORPUSCULAR FLUX	SOLAR COSMIC	
CHARGED PARTICLES		
NEUTRONS		
METEORIC FLUX	SOLAR SYSTEM	

For the moment attention will be focused on the lunar surface and those parameters which may be of importance in describing the surface. A possibly useful set of surface parameters is shown in Table II. As just mentioned, the surface may have deposits of meteoric iron or other material in an elemental state not possible on earth because of oxidation by the earth's atmosphere. Certain conditions of lunar mineralization may indicate the presence of water; this possibility is particularly feasible in regard to radioactive elements, and in Table II, surface radioactivity is explicitly mentioned along with densities, compositions, and concentrations. Lunar radioactivity due to uranium, thorium, and potassium is not expected to exceed a few milliroentgens/ week (total exposure of 100- to 200- roentgen skin dose is held acceptable).Thermal conductivities, heat capacities of lunar material, and subsurface temperature profiles are of interest in lunar technology as well as in lunar science. This is also true of the surface electrical properties which may make radio communication by means of ground wave propagation feasible. Lunar thermal extremes seem to be well established, ranging from approximately 120 to 400°K. Soil mechanical parameters, listed for completeness, may become less important as lunar exploration develops. Finally, in addition to the incident radiations mentioned in Table I, attention should be given to secondary, or reflected, radiations from the lunar surface. Some investigators feel that the mass of meteoric secondaries - that is, fragmented lunar material ejected from the surface by the impact of a primary particle - may exceed the primary mass by a factor [2,3] as great as 10^3.

TABLE II. SURFACE PARAMETERS

DENSITY
COMPOSITIONS AND CONCENTRATIONS
RADIOACTIVITY
THERMAL CONDUCTIVITIES
HEAT CAPACITIES
ELECTRICAL CONDUCTIVITIES
PERMITTIVITIES
SURFACE CHARGES
PERMEABILITIES OR MAGNETIC SUSCEPTIBILITIES
SURFACE STRUCTURE (GEOLOGICAL)
SOIL MECHANICAL PARAMETERS
BEARING STRENGTHS
FRICTION COEFFICIENTS
PENETRABILITIES
SHEAR STRENGTHS
COHESION COEFFICIENTS
TEMPERATURES AND THERMAL PROFILES
REFLECTED AND EMITTED ELECTROMAGNETIC RADIATION
SECONDARY EMISSIONS
CHARGED PARTICLES FROM ATOMIC AND NUCLEAR REACTIONS
METEORIC SECONDARIES

Of all the observations which may be made upon the lunar surface, those encompassed by the broad term "lunar geology" or selenology, probably require the most extensive background and the greatest number of immediate (in the field) decisions to realize an efficient program. The actual procedure to be followed at any particular site must be a function of the site and the astronaut's judgement; however, primary geological factors are indicated in Table III. The scope of this discussion presents a detailed discussion of Table III, which must be regarded as indicative rather than explicit. However, one should notice an approximate horizontal correlation in that subdisciplines in the left hand column apply to the geological entities in the right hand column. Mineralogy and texture parameters, in addition to simply defining composition, should also specify granulation, agglomeration and/or mixture, and microstructure. A geological unit is a block composed throughout of the same type of rock and structure; the term is useful as the nature of rock often changes very abruptly at unit boundaries known as contacts. One broad objective of the geological studies will be to define the location, extent, orientation (relative to some fixed direction) and other features of the unit configurations. Once some grasp of the local geology (or selenology) is obtained, hypotheses may be formulated as to the nature of the processes which are, and were, responsible for the observed states. Ideally, independent checks upon these hypotheses should be made. Finally analytical photographs and samples should be taken.

TABLE III. GEOLOGICAL DISCIPLINES AND FACTORS

GEOLOGICAL DISCIPLINES	GEOLOGICAL ENTITIES & PARAMETERS
STRUCTURAL GEOLOGY	MOUNTAIN RANGES, VALLEYS, FOLDS, CRATERS (IMPACT OR VOLCANIC)
STRATIGRAPHY	FAULTS, JOINTS, FORMATIONS UNITS AND CONTRACTS
GEOMORPHOLOGY	TEXTURE
PETROLOGY	FABRIC
MINERALOGY	CRYSTAL STRUCTURE
OPTICAL MINERALOGY	COMPOSITION
PETROGRAPHY	PHYSICAL PROPERTIES
	IDENTIFICATION

Having examined the basic physical parameters of the moon, attention can now be given to more complex geophysical-geodetic (or selenophysical-selenodetic) entities which may be possessed by the moon. These are listed in Table IV. Obviously the moon does possess angular momentum and is sufficiently stable in its orientation so that the concept of a lunar axis of rotation is useful. Due to the eccentricity and inclination of the moon's orbit about the earth and small perturbations of the moon's motion, the moon as seen from the earth oscillates in both longitude and latitude. These motions have never been completely comprehended theoretically and it is felt that a few hours of theodolite observations from the lunar surface would tell us more about the moon's motion than man has been able to acquire in several centuries from terrestrially based studies.

TABLE IV. GEOPHYSICAL ENTITIES AND GEODETIC PROPERTIES

LUNAR ANGULAR MOMENTUM AND AXIS OF ROTATION
LIBRATION PHENOMENA
ATMOSPHERE
IONOSPHERE
BIOZONE
MASS DISTRIBUTION
FIGURE OR SHAPE OF THE MOON
DEPTH PARAMETERS
COMPOSITION, TEMPERATURE, SEISMOLOGY, DENSITY AND ELASTICITY
GRAVITY FIELD
MAGNETIC FIELD
ELECTRIC FIELD

Another geophysical entity perhaps possessed by the moon is an atmosphere. Certainly any lunar atmosphere must be extremely tenuous; however, there are observations of apparent vapors, "mists," and hazes which suggest the presence of an atmosphere. These are probably not in the strict sense associated with an atmosphere of fairly constant composition and density. The recent significant and generally accepted observations, such as those observed near Aristarchus in the fall of 1963, indicate that free gases on the moon are a highly transitory phenomenon; however, an alternative explanation for these phenomena is lunar luminescence, to be explained subsequently. One component of the lunar atmosphere may be hydrogen arising from proton bombardment; other suggested constitutents are argon, radon, helium, and carbon dioxide - all arising from outgassing processes of lunar crust.

Since the moon is subjected to both corpuscular and ultraviolet radiation, it is reasonable to conjecture that there may be a lunar ionosphere and electrical charges upon the lunar surface. Electron densities [4] arising from photoionization are felt to be no more than 10^3 to $10^4/cm^3$. As for a surface electrical field, this would be a necessary concomitant of most lunar ionosphere models. At the present time there is no direct evidence indicating the presence of either an ionosphere or field.

More exciting, but of an even more controversial nature, is the possibility of past or present lunar life. Some theories - not generally accepted - postulate the existence on the moon of a layer [5] of organic material perhaps some ten meters or so below the surface. This "biozone" might contain life, evidence of past life, or biochemical precursors to life. Such speculations are intimately involved with current studies on alleged organic material within meteorites, and the hypothesis of "Panspermia"[6, 7], which asserts that living spores can endure the rigors of space and are propagated through it.

The distribution of lunar mass and the shape of the moon are fundamental to selenodetic studies. Correlated with information related to conditions in the moon's interior, such as composition, thermal regime, and seismic behavior, they can provide great insight into questions concerning the origin of the moon and the solar system, and the nature of geodetic processes. Studies of lunar gravity on the moon will provide corroborating data for other selenodetic investigations, just as terrestrial gravity surveys do for geology and geodesy.

The meager evidence available relative to the existence of a lunar magnetic field suggests that the lunar field [8] could be no more than a few 10^{-4} gauss (i.e., a thousandth that of the earth). Other data not generally accepted suggest to some that the moon does have an appreciable magnetic field.

Table V is a tabulation of those physical processes which are felt most likely to occur on the moon. That some of these phenomena do occur is a virtual certainty - e.g., impact cratering and nuclear reactions; other processes such as thermal cycling (i.e., the breaking up of rock under abrupt changes of temperature) and gravitational heating (explained later) are more doubtful. Sintering is

TABLE V. PHYSICAL PROCESSES

EFFECTS DUE TO:

- PARTICULATE (INCLUDING METEORIC) RADIATION:
  - IMPACT CRATERING AND COSMIC DUST EROSION
  - SEISMIC
  - SINTERING AND SPUTTERING
  - ATOMIC AND NUCLEAR REACTIONS
  - LUNAR LUMINESCENCE
  - POSSIBLE DARKENING OF MATERIAL WITH EXPOSURE TIME
  - PRODUCTION OF HYDROGEN
- ELECTROMAGNETIC RADIATION:
  - THERMAL CYCLING
  - CHARGING OF DUST
- POSSIBLE DARKENING OF MATERIAL WITH EXPOSURE TIME

GEOPHYSICAL:

- VOLCANIC
- SEISMIC (INTERNAL)
- GEOCHEMICAL
- TIDES
- GRAVITATIONAL HEATING

the fusing together of materials in contact on the moon under the combined influence of high vacuum and charged particle bombardment. Sputtering is an erosion of the surface being bombarded, in this case by charged particles; one estimate is that something like 17 cm [9] of the lunar surface have been lost by sputtering during the estimated life of the moon. Impact cratering is unavoidably suggested by the most casual examination of the lunar surface; erosion by the impact of cosmic dust, meteorites, etc., may be the single most active selenological process modeling the lunar surface. Seismic activity would seem a necessary phenomenon accompanying the impact of large meteoric bodies such as must have occurred in the past. While not as spectacular per event, elementary particulate bombardment and the effects of electromagnetic radiation may be just as important in the evolution of the lunar surface. Lunar atomic and nuclear reactions must undoubtedly be initiated by cosmic rays, particulate and electromagnetic radiation. Proton bombardment of the lunar surface quite possibly results in lunar luminescence and extensive radiation damage to crystal structures. The former, lunar luminescence, is the emission of electromagnetic radiation of a non-thermal origin, in this case the energy of the proton beam; the latter, essentially a reordering of crystal structure, may provide an explanation of the darkening of lunar features with time. Of perhaps special interest in the generation of a lunar atmosphere is the possible production of hydrogen by the neutralization of protons incident on the lunar surface. The presence of hydrogen might be established most easily by looking for Lyman-Alpha radiation, a characteristic emission of hydrogen, originating from directions other than that of the sun, of which hydrogen is the primary constituent.

Due to the lack of a substantial atmosphere to delay the cooling or heating of the lunar surface, temperature changes in surface rocks upon the transition from lunar day to lunar night and vice versa, must be quite abrupt. On the earth this "thermal cycling" causes considerable weathering; however, it is uncertain whether over astronomical periods of time this could be a major factor in the weathering of rock as nearly free of water as lunar material is thought to be. Under irradiation by the solar ultraviolet, the charging of dust is quite possible; just how extensive such charging is and whether it is a mechanism for the transport or flow of lunar dust is uncertain. One effect already mentioned, seemingly well established and apparently associated with exposure to electromagnetic and/or particulate radiation, is that of the darkening of rays with time; the older a crater, the darker and the less conspicuous its rays. The brightest areas on the moon are the ray material of the most recent craters.

Other geophysical or selenophysical phenomena of controversial importance are listed in the last group of Table V. Some investigators believe that lunar vulcanism is at least as important in the formation of the observed lunar surface as impact cratering; others feel that most volcanic activity arises from-that is, is triggered by impact phenomena. In any large body still cooling, or containing sources of internal heat such as radioactive elements, internal seismic activity is to be expected. Furthermore the presence of heat suggests that portions of the moon may be molten, or that there may be water and steam in the interior. These factors, along with natural radioactivity, must give rise to a complicated regimen of geochemical effects. Other than moonlight itself, the best known effect of the moon on the earth is that of oceanic tides. Conversely, although the moon has no seas, the earth very probably causes a lunar crustal tide [10] on the moon whose magnitude may be several centimeters. Furthermore, unless the moon is very rigid, its libratory motions, in addition to causing surface tides, must be associated with periodic gravitational deformations of the moon which to a degree varying with the lunar viscosity result in gravitational energy being converted into internal heat. This is called gravitational heating.

Mission Composition and Profile

Having made a brief survey of the kinds of physical phenomena which may be expected on the moon, one may now conceive of the broad features of a lunar scientific mission whose objectives would be to obtain scientific information of the sort just considered.

The resources assumed available for the mission can be categorized as follows:

Vehicles consisting of an Apollo Command and Service Module, a Lunar Excursion Module (LEM) and a LEM truck serving as a cargo vehicle and delivering a mobile laboratory known as MOLAB to the lunar surface some months prior to the manned landing. The command service module complex enters into an orbit around the moon and carries either a LEM or LEM-Truck on two separate flights. The LEM-Truck will land on the moon and several months later a manned LEM will land. Upon completion of the mission, the crew returns to orbit in the LEM and performs rendezvous with the command- service module. The LEM is then abandoned as is the service module after injection into earth orbit; only the command module returns to earth.

Supplies and scientific instrumentation.

Men familiar with contemporary science - preferably scientists able to exploit any serendipitious phenomena.

Earth-based communications.

Observations will begin with the orbiting of the Command Module delivering the LEM Truck with its MOLAB cargo - particularly, high resolution photography for the preparation of photogeological maps to be used in subsequent manned landings. Observations will also be made from the Command Module of the manned landing operation for two weeks with one man aboard after two men descend to the lunar surface in the LEM. The sole occupant of the Command Module should be kept busy for psychological reasons and for achieving the scientific objectives of the mission. On the lunar surface the range of the MOLAB will be assumed to be about 350 kilometers and the duration of the mission two weeks, so chosen as to provide experience with both lunar day and lunar night operations.

Many considerations must enter into the planning of this mission's activities. All feasible scientific measurements and observations must be considered with respect to relative scientific importance; usefulness for the planning of future lunar operations; requirements in terms of instrumentation, power, telemetry, and operator sophistication; and compatibility with other experiments. Then decisions (to some extent arbitrary) must be made as to the relative priorities of all the various studies one might make of the moon. Instrument evaluation includes, among many other things, consideration of any special environmental sensitivities of proposed instrumentation and possible breakdown modes.

In considering measurements and observations, decisions as to what experiments to include are only the beginning. For any given measurement one next ponders, "Is this to be a continuous observation (e. g. micrometeoroid flux) or one made only at discrete intervals (e. g. temperature)? Or should it perhaps be done just once (e. g., atmospheric composition prior to contamination by man)? Is this observation to be made at different places (e. g., geology)? When one takes a sample, is he sampling for composition or structure?"

The preservation of both purity and structure may not be possible for an individual sample. Some observations (e. g., the lunar gravity field) are intimately associated with the moon and can be made nowhere else; others can be performed better in earth laboratories provided that excellent samples are obtained. The preservation of strict purity in samples will probably require their being placed in containers thoroughly outgassed during transit in space or on the lunar surface, since the moon's atmosphere may be more rarefied than the best vacuums attainable on earth. To preserve the sample structure may require the use of special potting or embedding compounds.

One operation involving sampling and observations is that of drilling. Drilling ten to thirty meters into the moon and extracting a core may be one of the most rewarding activities; certainly it will be among the most difficult because only a limited mass can be allocated for drilling equipment. Once a hole has been drilled and core samples extracted, one may study radioactivity, thermal and electrical properties as functions of depth beneath the lunar surface. Finally the hole may be useful as a means for generating seismic waves within the lunar crust by means of explosive charges detonated in the hole; both refraction and reflection profiles, as dictated by the surface geology, could be included in a program of observations.

Reflection upon the kinds of observations and their scheduling leads to the recognition of broad categories. If one assumes initially no further knowledge of the moon than that which is current, the first category of observations consists of those which might be made from the Command Module performing the delivery of the LEM Truck with the MOLAB. As previously suggested, this Command Module could orbit the moon several times giving particular attention to high resolution photographic studies of the landing site and the area to be examined by the MOLAB on its 300 to 400 kilometer geophysical traverse.

It is desirable that the MOLAB-LEM Truck complex be used for valuable observations during the interim between the delivery of the MOLAB and the landing of men several months later. The instrumentation and associated telemetry for these observations would form a complex which might be called an Emplaced Instrument Complex (EIC), in that it would function as an unmanned station monitoring lunar phenomena both before and after the arrival of man. Command Module observations and possible experiments for inclusion in the EIC are listed in Table VI. The philosophy employed in selection of these experiments is that of directly evaluating all conceivable hazards to manned operations, or of measuring lunar properties whose later study may be difficult due to contamination. An atmospheric spectrometer is suggested because the rocket exhaust from a single LEM landing may amount to a significant fraction of the total lunar atmosphere. Cold welding is the joining of contiguous surfaces under conditions of high vacuum and/or bombardment by charged particles; should this tend to occur, any manned mission might be seriouly inconvenienced if not actually threatened with disaster. Accordingly a cold welding experiment is suggested in order to acquire the knowledge of the likelihood of such effects before committing men to the lunar surface. In addition to these experiments, the astronauts may install other instruments after their arrival. Before their departure the astronauts should do all that is reasonably possible to make the EIC into a well functioning unmanned geophysical observatory which will provide information long after the return of the expedition.

Upon the arrival of men on the lunar surface via a LEM landing in the vicinity of the LEM Truck, and after a checkout of the MOLAB and EIC, the MOLAB will proceed on the geophysical traverse. This traverse will result in the establishment of a series of geophysical-geological stations whose selection will be dictated by the particular nature of those selenological features lying

TABLE VI. SCIENTIFIC MEASUREMENTS AND OBSERVATIONS PRIOR TO MANNED LANDING AND POSSIBLE EXPERIMENTS FOR EMPLACED INSTRUMENT COMPLEX

LEM TRUCK COMMAND MODULE OBSERVATIONS (FROM LUNAR ORBIT)

(RESULTS OBTAINED BEFORE THE DELIVERY OF THE LEM TRUCK COULD INFLUENCE CHOICE OF LANDING SITE.)

- HIGH RESOLUTION PHOTOGRAPHY
- PRIMARY METEORIC RADIATION (POSSIBLY)
- RADIOACTIVITY SURVEY (POSSIBLY)

EMPLACED INSTRUMENT COMPLEX (ON LUNAR SURFACE)

BEFORE MANNED LANDING INSTRUMENTATION TO MEASURE:

- TOTAL METEORIC RADIATION
- CORPUSCULAR RADIATION
- GAMMA RADIATION
- THERMAL ENVIRONMENT
- ATMOSPHERIC COMPOSITION
- ELECTRIC FIELDS
- MOON QUAKES
- COLD WELDING

ADDITIONAL INSTRUMENTS TO BE INSTALLED AFTER MANNED LANDING

- TIDAL GRAVIMETER
- LYMAN ALPHA RADIATION DETECTOR
- THERMAL CONDUCTIVITY PROBES

within 150 to 200 kilometers of the landing site. The track of this initial lunar traverse should be planned such that at all points the remaining travel capability in terms of time and fuel always exceeds the travel necessary to return to the landing site on a previously traveled path; otherwise the expedition might find itself in a cul-de-sac from which escape would be impossible. This requirement leads to topological "figure 8" and "cloverleaf" tracks; once the hazards of lunar exploration are better understood, this restriction may be relaxed. Routine observations for a geophysical station are listed in Table VII.

In addition to the observations performed by the EIC and those to be made at all geophysical stations, there are elective observations (see Table VII) which the astronauts may feel worthwhile in response to local selenological features or physical events (e.g., passage of the terminator). Drilling, the shooting of seismic profiles, or the detailed study of subsurface geology as it might be revealed in a fissure are prime examples of important but very time consuming elective observations. Sampling for both the typical and the unusual is an elective observation par excellence. Another example is that of encountering an active fumerole in whose mouth a gas chromatograph might be emplaced to identify gases being released from the lunar interior; chromatographs might also be used electively to analyze samples for rare volatiles more effectively under the high lunar vacuum than such analysis could be done on the earth.

Finally there are those observations which can be made from the orbiting Command Module in which the three-man expedition will return to the earth. This orbiting body provides an excellent station for some geophysical observations which hardly would be feasible by any means other than an orbiting laboratory. High resolution photography can be performed on a substantial portion of the lunar surface, including the back side. Other measurements indicated in Table VII include thermal mapping (i.e., infrared radiations) of the lunar surface, studies of lunar luminescence, lunar magnetism, meteoric primary radiation, and radioactivity surveys. Due to the tenuous (if any) lunar atmosphere the range of radioactive particles emitted from the surface will be measured in hundreds of kilometers rather than in centimeters as is the case on the terrestrial surface. The precise shifting of the Command Module's orbit and its period might provide valuable selenoditic information if the orbit is of high inclination; relatively high inclinations may appear more feasible after the initial Apollo landing.

This paper is intended merely as an introduction to a lunar scientific mission. While perhaps many points have been raised upon which elaboration would be desirable, nevertheless it is hoped that the ideas presented here are sufficient to give some insight into the philosophy of planning such an expedition, and that they will serve as a stimulating guide to further thinking on lunar exploration.

TABLE VII. POSSIBLE OBSERVATIONS AND MEASUREMENTS FOR THE LUNAR GEOPHYSICAL TRAVERSE AND ORBITING COMMAND MODULE AFTER MANNED LANDING

ROUTINE GEOPHYSICAL STATION OBSERVATIONS

- GEOLOGICAL TRAVERSE OF SMALL SELECTED AREAS
- SPECTROPHOTOMETRY OF {INCIDENT / REFLECTED / EMITTED} {U. V. / VISIBLE / INFRARED} RADIATION
- SURFACE RADIOACTIVITY
- GRAVITY
- MAGNETIC FIELD
- ELECTRIC FIELD
- THEODOLITE STAR TRACKING

MOLAB ELECTIVE OBSERVATIONS

- SAMPLING
- DRILLING INCLUDING: CORE EXTRACTION AND ENCAPSULATION RADIOACTIVITY MEASUREMENTS THERMAL AND ELECTRICAL PROBING REFRACTION-REFLECTION SEISMOLOGICAL
- GAS CHROMATOGRAPHY AND ANALYSIS OF RARE VOLATILES
- PHOTOGRAPHY
- SOIL MECHANICS
- PRECISE DESCRIPTION AND ANALYSIS OF ANY UNUSUAL PHENOMENON OR FEATURE

TABLE VII. POSSIBLE OBSERVATIONS AND MEASUREMENTS FOR THE LUNAR GEOPHYSICAL TRAVERSE AND ORBITING COMMAND MODULE AFTER MANNED LANDING (Concluded)

LEM COMMAND MODULE OBSERVATIONS
HIGH RESOLUTION PHOTOGRAPHY
THERMAL AND ULTRAVIOLET MAPPING OF MOON
RADIOACTIVITY SURVEY
METEORIC PRIMARY RADIATION
MAGNETIC FIELD
LUNAR GEODESY FROM ORBITAL MECHANICS

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Chapter 2

SOME SUGGESTED LANDING SITES FOR EXPLORATION OF THE MOON

By

Daniel Payne Hale *

The purpose of this paper is to present a representative selection of landing sites for scientific exploration of the moon; the selection given here is by no means exhaustive, nor does it include all of the most interesting sites. Furthermore, many of the assertions frequently made about sites such as conditions that may prevail and adjacent topographic features, are quite conjectural. Bearing this in mind, one can proceed without further ado.

Lunar nomenclature is delightful, and an interesting treatise could be written on the origin of lunar names alone. Viewing the full moon and dividing the circle by a north-south diameter into an eastern and a western half, we find in the western** half such names as the

Sea of Honey (Mare Nectaris)
Sea of Tranquillity (Mare tranquillitatis)
Sea of Fertility (Mare Fecunditatis)
Sea of Crisis (Mare Crisium)
Sea of Serenity (Mare Serenitatis)
The Lake of Dreams (Lacus Somniorum)
Sea of Cold (Mare Frigoris)
Sea Vapors (Mare Vaporum)

In the eastern half, one finds names pertaining to water in various forms such as

Sea of Rains (Mare Imbrium)
Bay of Rainbows (Sinus Iridum)
Marsh of Decay (Palus Putredinis)
Sea of Clouds (Mare Nubium)
Sea of Moistures (Mare Humorum)
Ocean of Storms (Oceanus Procellarum)
Marsh of Diseases (Palus Epidemiarum)

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** i.e., to the right of an observer viewing from the northern hemisphere. For an observer at the center of the visible lunar circle, this (western) half is to his east.

However suggestive and charming these names may be, a somewhat more analytical approach is needed to study the moon. One can begin by listing the major kinds of lunar topographical features. An elementary observation, obvious on one's first encounter with the moon, is that some areas are darker than others. The dark areas are known as maria; they are frequently circular or polygonal in shape, and are generally of a smoother topography than the brighter, higher areas known as terrae. Both maria and terrae may contain a variety of smaller features; specifically, one finds:

- Domes - primarily mare features
- Wrinkle Ridges - winding elevations perhaps arising from compression, present in the maria
- Craters - of either impact or volcanic origin, sometimes occurring in chains
- Rays - conspicuous radial features diverging from some craters
- Cones - apparently arising from plutonic activity in some craters
- Cracks - often extending for kilometers
- Faults - fractures in which there has been relative displacement of the separated parts
- Depressions - of kilometer dimensions
- Rilles - relatively narrow, winding depressions
- Valleys and Scars - many of these radiate from the Sea of Rains as though gouged out by flying debris.

In selecting landing sites for exploration of the moon, factors of importance are:

1) Possibilities for a smooth landing area and the traversability into the surrounding areas

2) The presence or absence of cracks which may afford protection against high temperatures, meteorites, and solar corpuscular radiations

3) The possible presence of minerals containing water of hydration and absorption. This water may not be of any use to an initial expedition, but knowledge of the location of such areas would be vital to the planning of permanent lunar bases. It is believed that volcanic craters are more likely to possess hydrous rock (perhaps 1% water by weight) than impact craters.

4) The proximity of a wide variety of lunar features.

5) Celestial mechanical considerations

6) The interests and preferences of the selectors.

In preparation of this paper, consideration was given to over thirty recommendations from five lunar geologists. Of all these suggested sites, only three were duplications. The sites to be discussed herein are a composite of the work of Shoemaker and Eggleton,[1] Dugan,[2] Green,[3] and Beattie.[4] The photographs used in this paper to illustrate the sites are taken from Kuiper's Atlas.[5] In examining these photographs one must bear in mind that it is impossible photographically to resolve clearly lunar detail smaller than about 3/4 kilometer. However, the eye can do better than the camera because terrestrial atmospheric disturbances which cause a smearing of the photographic image do not nearly so confuse the brain which can remember what the eye has seen just before a disturbance, and can correlate it with the present image. Therefore, features mentioned in the following descriptions would be more prominent to an observer viewing the moon than they are in a photograph taken through the same telescope. Furthermore, the visibility of lunar features is a sensitive function of the angle and intensity of illumination; thus few areas, if any, of the moon are such that all features of interest simultaneously achieve their most conspicuous aspect for any one condition of illumination. The present site selections have been made on the basis of surveys conducted under many different conditions of illumination; still one has good grounds for skepticism about authoritarian pronouncements regarding the roughness of lunar terrae on a scale comparable to the size of a man.

In the figures each site is marked by a black circle containing a star; each figure contains an arrow of length corresponding to 35 kilometers on the lunar surface, pointing approximately to the center of the full moon as seen from earth. The top edge of each figure is oriented toward lunar south with the other directions corresponding to the usual convention. Before examining the sites in detail the reader should glance at Figure 1 which shows the whole moon and all the sites to be discussed. One can begin in the lunar* north northeast and work across to the west and to the south. Also indicated in the figure are the impact sites of the Ranger VII, VIII, and IX spacecraft, which provided closeup pictures of the moon's surface.

Commentaries on each of twenty-five nonpolar sites follow, and generally there is one figure for each site, although some figures contain two or three sites. In preparing these brief discussions, consideration was given to all six

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* Lunargraphical coordinate system is similar to that used on earth; its axis is the lunar axis of rotation. This is not the same system mentioned in the second paragraph of this paper.

FIGURE 1. MAP OF THE FULL MOON

site selection factors listed above; however, the proximity of a variety of interesting lunar features is the dominant consideration. Photographs of the nonpolar sites appear in Figures 2 through 18.

Site 1 RUMKER HILLS IN WESTERN MARE IMBRIUM (Figure 2)

The "Hills" are dome-like features extending from north to south for a distance of about 65 km and are thought possibly to be of volcanic origin. Within about 10 km of the landing site shown on the map, there is an impact crater of about 5 km diameter. The dome complex displayed here is known nowhere else on the moon; the wrinkle ridges here may be evolving into domes. Good traversability is expected. Shelter and hydrous rocks may be found in the hills.

Site 2 ON A SUSPECTED FLOW IN MARE IMBRIUM (Figure 3)

This is a low plateau suggesting a solidified flow of basalt. Fifty kilometers to the east is the edge of the plateau. A crater over 5 km in diameter is about 24 km to the southwest; this crater is rayed in its northwestern quadrant, but is otherwise unrayed. There are undulations suggesting a wrinkle ridge complex, and the presence of ray material, apparently from Copernicus over 600 km distant, should be noted. The mare material should afford traversability and possibly shelter.

Site 3 ON MARE IMBRIUM NEAR SPITZBERGEN MOUNTAIN MASS (Figure 3)

The Spitzbergen massif effectively rings a basin some 8 km to the east; eight kilometers to the west there is a ridge of mare material which is cracked along its crest. The crack should offer shelter and opportunity to examine the subsurface geology. West of the site there is a large depression. As usual, good traversability is expected on the mare surface.

Site 4 LINNE (Figure 4)

This is an extremely interesting area, if earlier observations are reliable. In 1824, Lohrmann of Dresden described Linne as "a deep crater visible under any angle of solar illumination," and his description was confirmed by Madler of Berlin in 1837. In 1866, Schmidt, observing from Athens, described Linne as "a whitish cloud." Goodacre in 1910 felt it to be "a cone on the edge of a shallow depression," while Wilkins and Moore in 1958 felt it to be a pit on the summit of a low dome - i.e., the reverse of a crater. Dugan has reported vapors and feels it is a white patch varying in size inversely as the surface temperature. One interesting feature of this series of observations is that they are progressive, specifically suggesting a crater which filled and became a cone. In the Linne area, there are two domes, extensive ridge systems, and a shallow ruined ring.

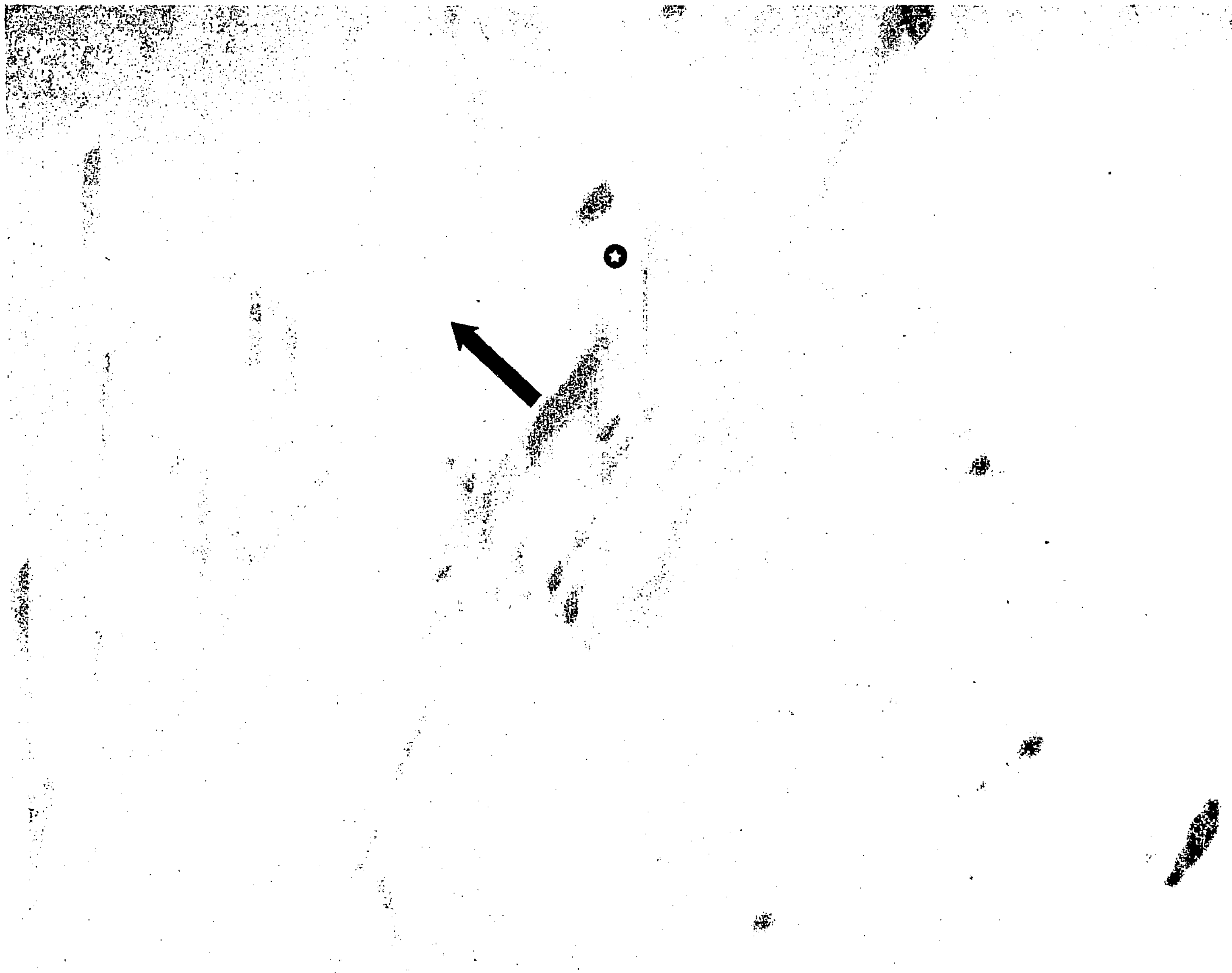

FIGURE 2. RUMKER HILLS

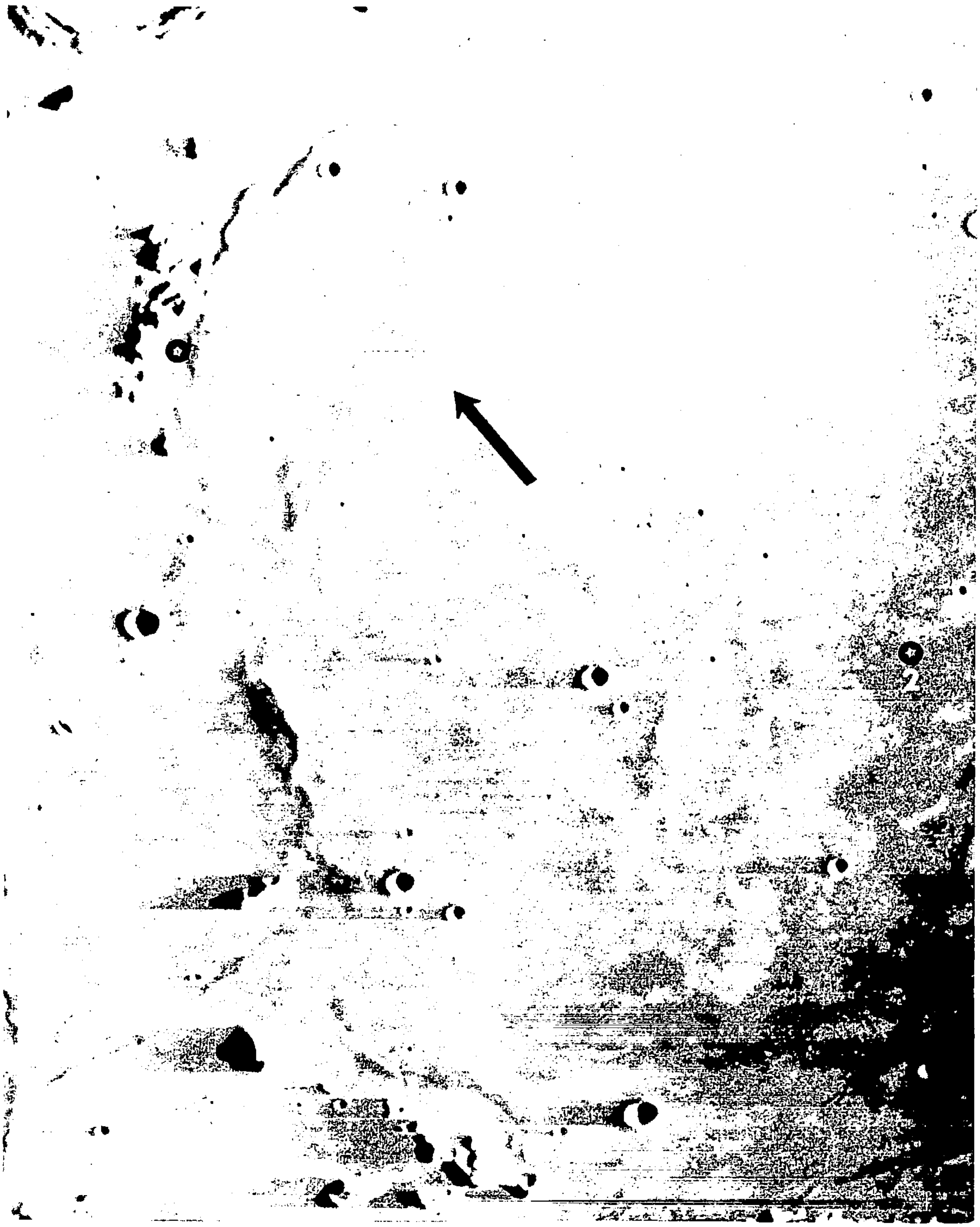

FIGURE 3. MARE IMBRIUM

FIGURE 4. LINNÉ

Site 5 ARISTARCHUS (Figure 5)

Among the most interesting areas on the moon, Aristarchus is a new crater adjacent to the older crater Herodotus. Aristarchus has a well defined rim, is rayed, and has a higher albedo than any known lunar feature. There is a central mountain of height approximately 350 meters with a crater pit on its summit. The northern wall of the crater opens into Schroter's Valley, one of the most interesting of the great lunar cracks and from whose southwest end vapor has been reported. There are many ravines and clefts, and the smooth mare of Herodotus's interior may afford a landing site. Aristarchus possesses dark bands which seem to have increased in visibility during the last 50 years; to some these bands seem to develop with the lunar day as though they were vegetation. On 30 October 1963, between 0150 and 0215 Universal Time, three red spots from 2 to 4 km in diameter were observed in the vicinity of Aristarchus; although many thought these might be lava pools, the most likely interpretation is that they were clouds of flourescing gas escaping from the lunar interior.

Site 6 BASE OF MT. HUYGENS (Figure 6)

This site affords access into the mountains to the east and into the Marsh of Decay lying some 100 to 150 km to the northeast; this latter feature seems to have been formed by an infilling of a great depressed area. Huygens' local altitude is around 5700 meters, making it the loftiest mountain of the Lunar Appennines; its steep slope facing Mare Imbrium may provide an informative geological cross section. The site is on the mare at the mountain's base, and was selected with the idea of affording an easy route onto Huygens.

Site 7 BETWEEN THE CRATER PLINIUS AND THE HAEMUS MOUNTAINS (Figure 7)

Plinius offers a variety of features including radial ridges, clefts, craterlets, a depression, and a dome with a craterlet; also noteworthy are the breaches to the north and south in the wall of the crater. Of especial interest in this area is the prominent color discontinuity between the Sea of Tranquillity and the Sea of Serenity.

Site 8 A DOME NEAR MILICHIUS AND TOBIAS MAYER (Figure 8)

The proposed site is a dome on whose top is a crater of 2 km diameter. The dome is semicircular, roughly 16 by 8 km, and is thought to bear some resemblance to terrestrial volcanic features. The southeast side of the dome joins a linear "mountain ridge" complex extending for about 20 km. Ridges may be remnants of walls. The site is on the rim of a very old crater existing prior to the laying down of the ray material.

FIGURE 5. ARISTARCHUS

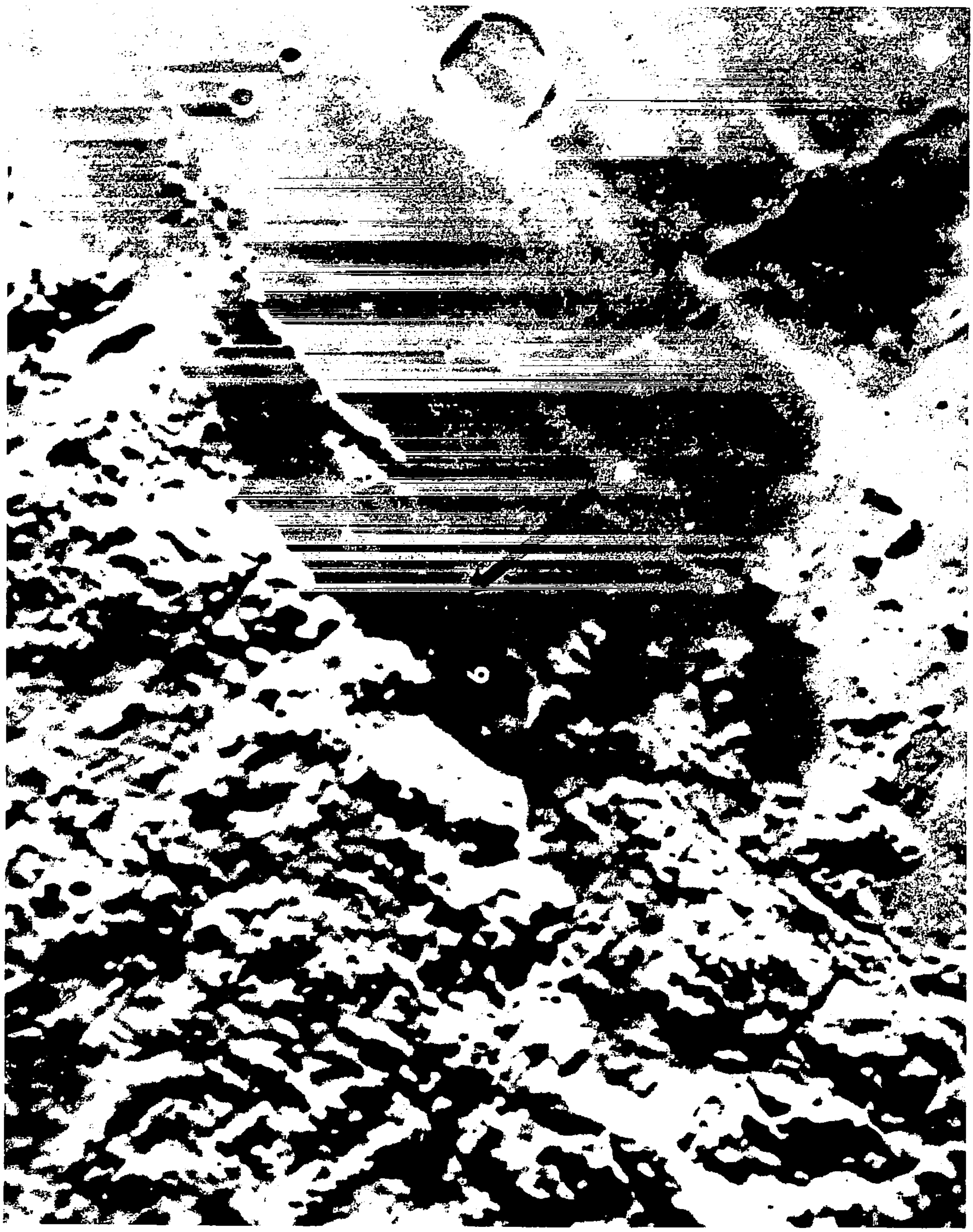

FIGURE 6. MT. HUYGENS

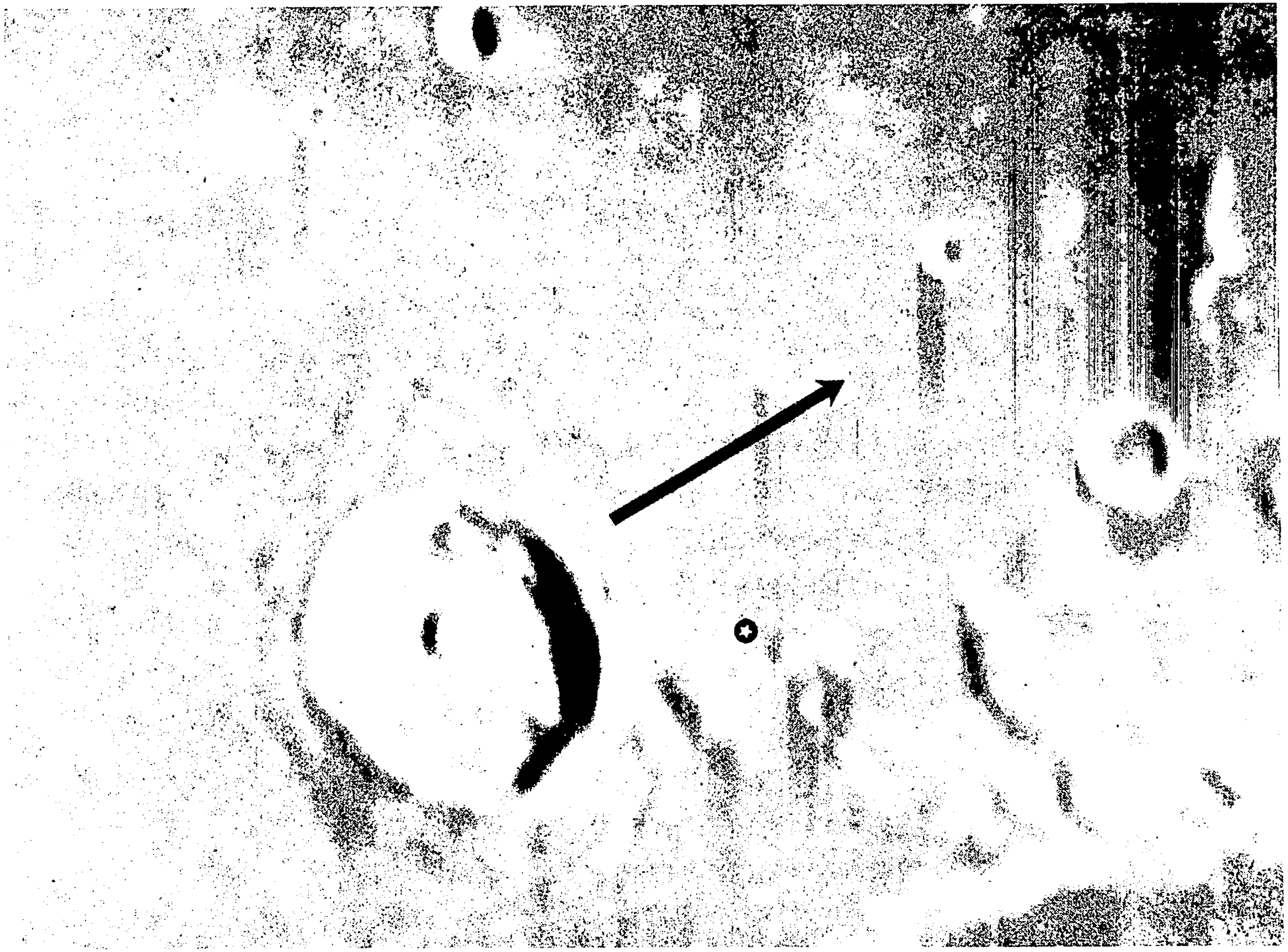

FIGURE 7. CRATER PLINIUS AND HAEMUS MOUNTAINS

FIGURE 8. COPERNICUS

Site 9 COPERNICUS NEAR THE CENTRAL PEAKS (Figure 8)

Copernicus is approximately 90 km in diameter and is thought to be one result of an impact which blasted material over an area whose diameter must be reckoned in hundreds of kilometers. The central mountains are all within about 15 km of the site, with the nearest part of the crater wall about 20 km to the west northwest. The floor of the crater should have fragments of material originating from several kilometers below the surface. Noteworthy is the hummocky topography about the crater and its terraces suggesting great slips. Traversability is probably difficult with little chance for hydrous rock.

Site 10 SMALL DEPRESSION 60 KM SOUTHEAST OF HORTENSIUS (Figure 8)

Of especialinteresthere is the rimless (not of impact origin) depression some 5 km or so southeast of the landing site. The depression is about 6 by 5 km and may be a collapse feature - in which case a vertical section of mare material might be conveniently exposed. The depression may also provide caves and hydrous rock. Twenty kilometers to the west northwest is Hortensius C, believed to be an impact crater. Seventy kilometers to the north northwest are the Hortensius Domes. Hortensius itself, a crater approximately 14 km in diameter, lies 50 km to the west northwest. Hortensius E, of diameter about 15 km, can be seen drowned in the mare some 4 km to the east southeast.

Site 11 KEPLER (Figure 9)

The Kepler crater is about 30 km in diameter. The area contains ridge features suggesting sculpturing by blast and blast shielding; a parabolic fan of apparently blast-shaped features is to the west. To the south is an area rich in a variety of geological features, perhaps containing an unusually large assortment of features for its area. To the south southwest some 90 km are chain craters and the crater Encke. Also of interest in this area is the appearance of concentric geological features.

Site 12 ON APPENINIAN MATERIAL 225 KM SOUTHEAST OF COPERNICUS (Figure 10)

Appeninian material, or the upland material about Mare Imbrium, is thought to be among the very oldest materials exposed on the lunar surface. The site is on one of the darkest materials of the moon, and the material at the site appears to be other than mare. Five km to the east is apparent mare material overlain by ray material. To the south southeast one may notice a small bright hill from which there diverge two ray features of lengths about 16 km; the location of the hill and the orientation of the rays suggest that the hill was hit by a fragment from Copernicus.

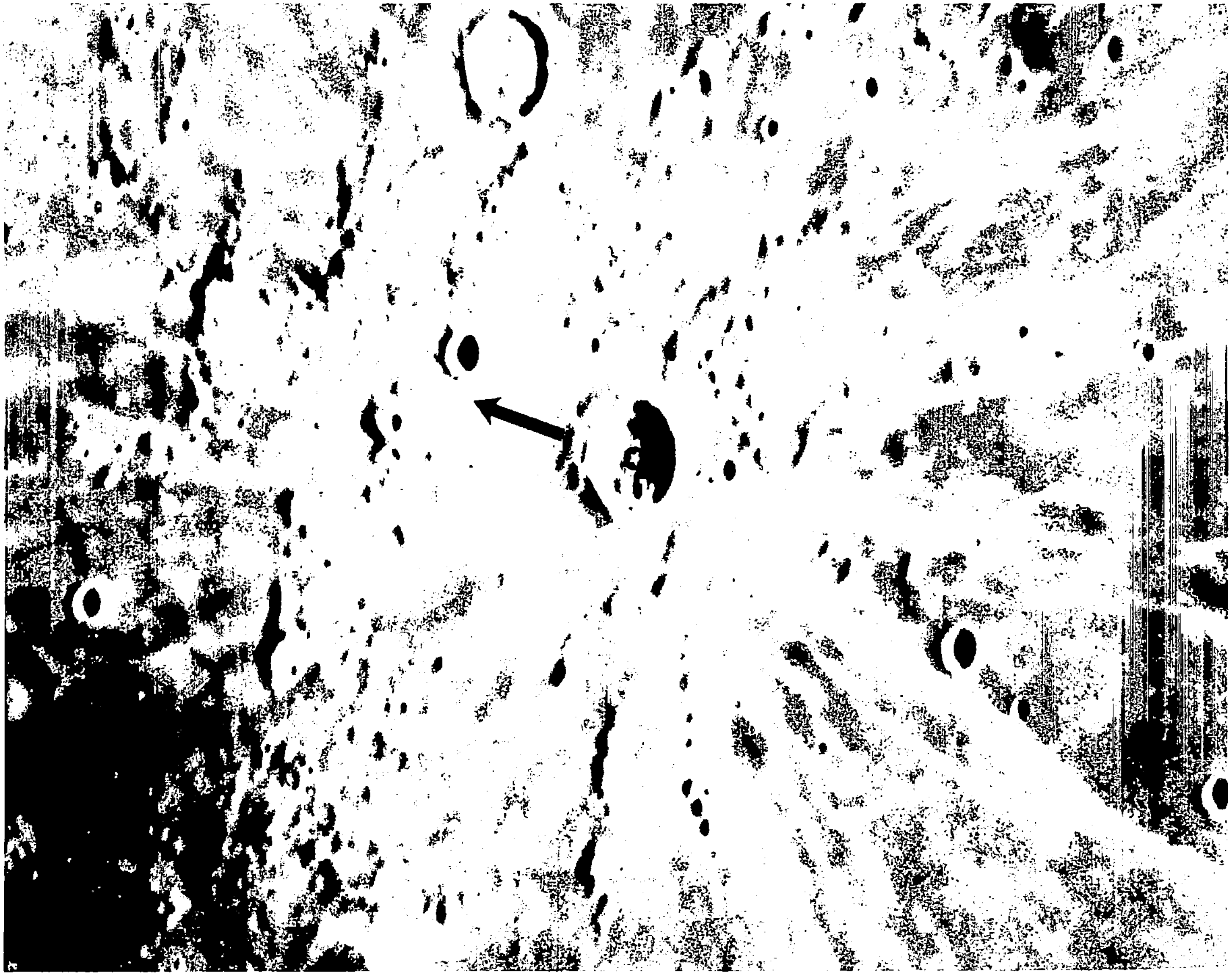

FIGURE 9. CRATER KEPLER

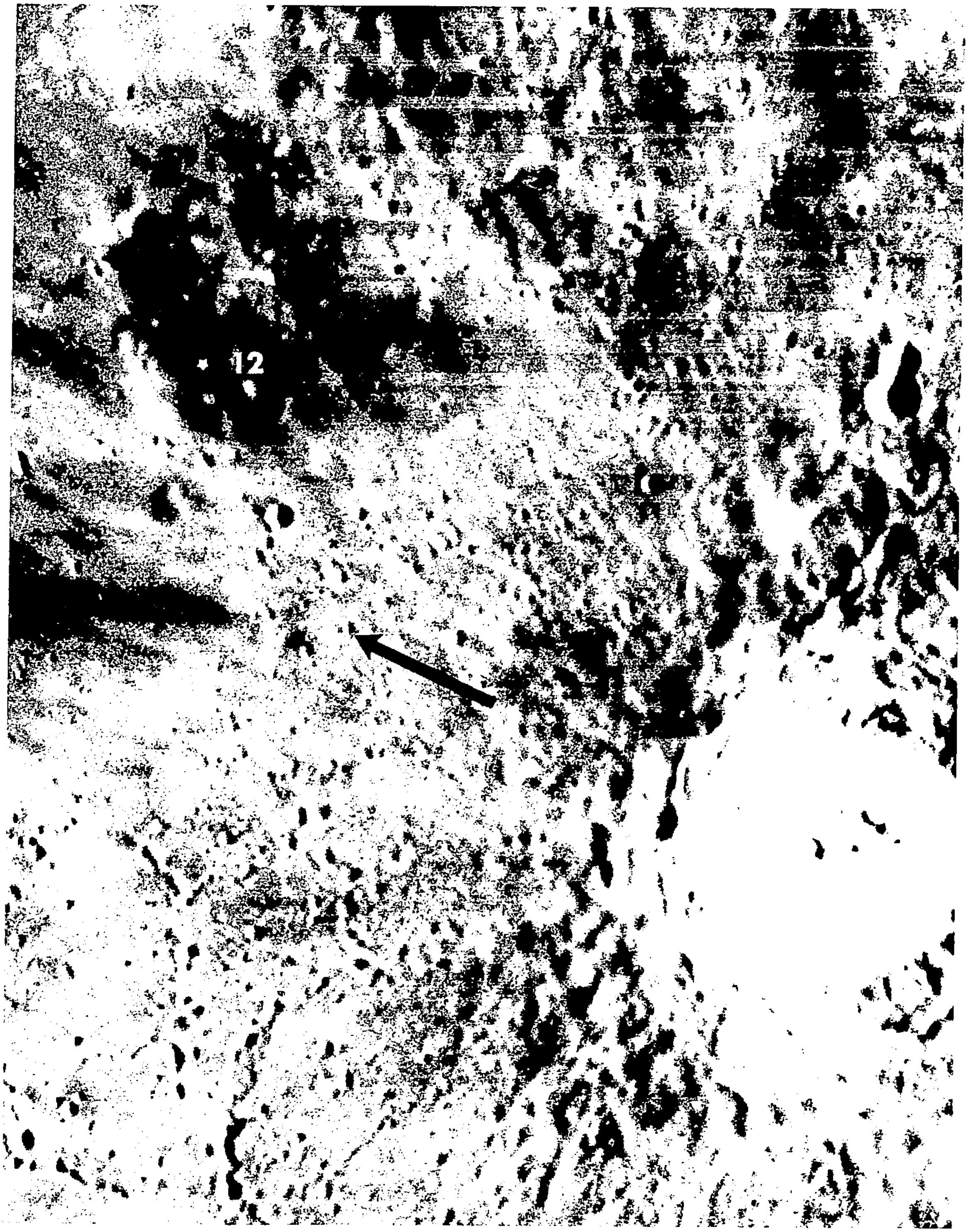

FIGURE 10. ON APPENINIAN MATERIAL NEAR COPERNICUS

Site 13 ON THE FLOOR OF THE CRATER HYGINUS (Figure 11)

Hyginus' diameter of about 7 km makes it one of the largest craters generally agreed to be of volcanic origin; possibly its ejecta may contain fragments from deep within the moon. The crater lies on the Hyginus Rille - a major lunar crack which passes through the centers of many craters. This rille is approximately 140 km long, and of width from 3 to 5 km; its walls may expose cross sections of the lunar surface. The Hyginus rille extends into the Ariadaeus rille; the area around this rille is generally smooth. However, to the west there is an extremely rough area with many cuts converging into Mare Imbrium.

Site 14 JUST NORTH OF CRATER FLAMSTEAD (Figure 12)

This site is within a very large (70 km diameter) old ruined ring containing several hills and a variety of craters. The height of the remanent walls of the old ring vary from 50 meters (southern rim) to about 330 meters (NW rim). That this region is deeply buried is indicated by the fact that a very large crater is almost completely covered.

Site 15 WICHMANN (Figure 12)

The site affords wrinkle ridges and a uniform level area among the smoothest areas on the moon.

Site 16 URAL MOUNTAINS (Figure 12)

In the vicinity of the site there are also the remanent Riphaean Mountains and portions of rings in the mare between the site and the crater Lansberg. Approximately 50 km to the southwest is a recent impact crater with a ray system.

Site 17 THEOPHILUS AND SOUTHERN END OF THE SEA OF TRANQUILITY (Figure 13)

Theophilus is similar to, but larger than, Copernicus with the exception that it possesses no rays. With a diameter of over 100 km, Theophilus has a tremendous central mountain mass with multiple peaks and structures suggesting buried rings. Theophilus obviously has intruded upon the older crater Cyrillus. The shadings on the margins of the Sea of Honey and the Sea of Tranquillity seem similar to terrestrial continental shelves. Of special interest is the terracing on, and the small crater within, the walls of the main crater.

Site 18 ON THE NORTH FLANK OF PARRY A (Figure 14)

The feature of primary interest is the rim of the crater Parry A which is even darker than surrounding material of Apenninian Age; this may be ejecta

FIGURE 11. CRATER HYGINUS

FIGURE 12. CRATER FLAMSTEAD, URAL MOUNTAINS, AND WICHMANN

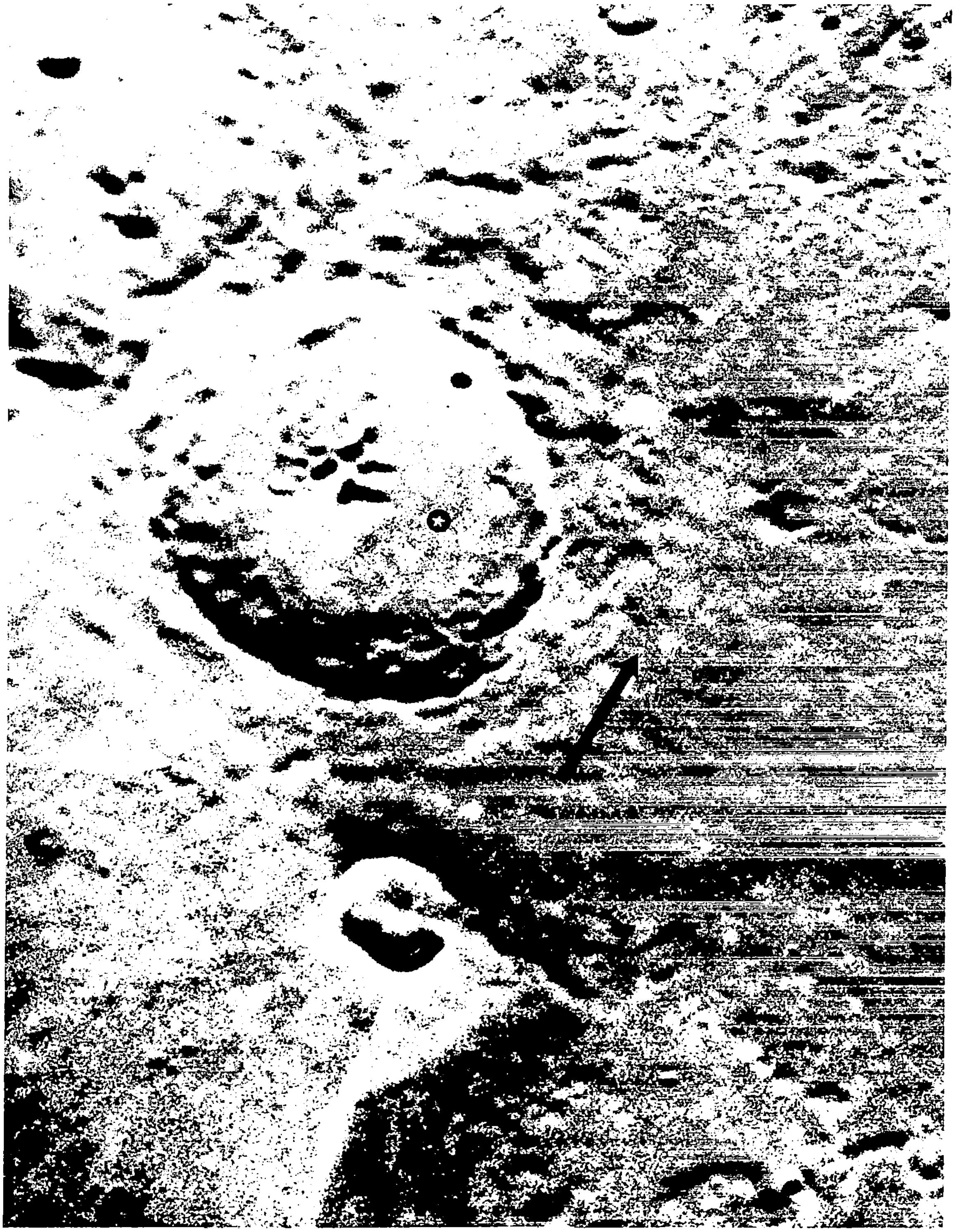

FIGURE 13. THEOPHILUS

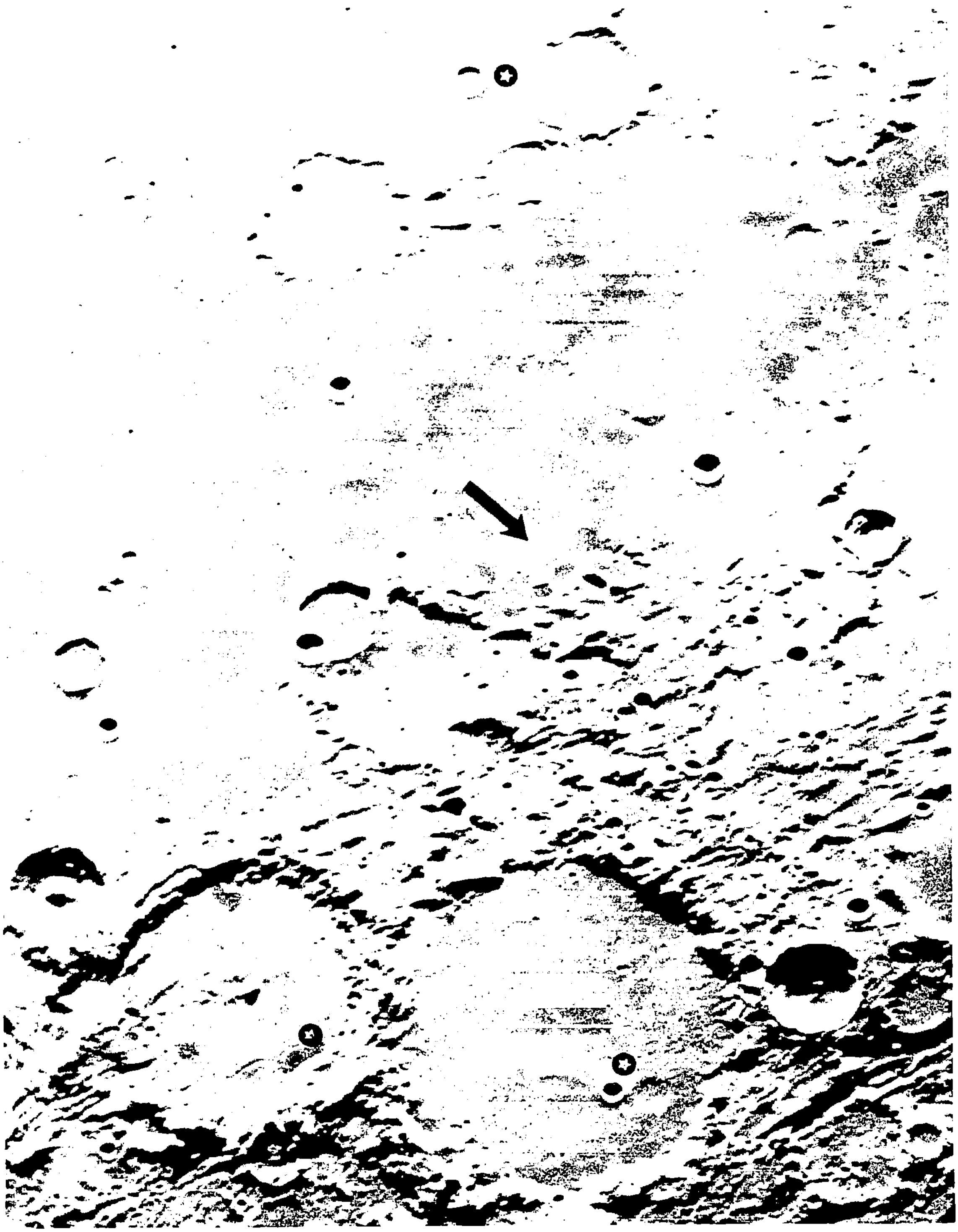

FIGURE 14. CRATERS PTOLEMAUS AND ALPHONSUS

from a layer of pre-apenninian, mare-like material. This older material does not seem to be exposed anywhere else on the moon. A few kilometers west of the site is a rille, perhaps affording shelter and exposed geology. In the general area can be seen streaks converging into Mare Imbrium.

Site 19 CRATER PTOLEMAUS (Figure 14)

The proposed site is in the interior of the crater, which contains many pits, craterlets, and ridges. A prominent interior crater is Lyot - very white and thought to be a crater-cone by some. There are also a number of shallow saucer-like depressions and an interesting cleft near the western wall.

Site 20 ON FLOOR OF ALPHONSUS (Figure 14)

Within Alphonsus there are seven small craters with dark halos suggesting that they are of volcanic origin. Through the center of the crater there is a rille of approximately 2 km in width running to the north beyond Ptolaemeus; to the South (or top of the figure) the rille becomes a ridge. Thirty kilometers southwest of the indicated site, there is a central peak which was the source of the gaseous emanations (perhaps C_2 and C_3) reported by Kozyrev in 1958. Apenninian material is exposed. The ridge and haloed craters may afford hydrous rock and shelter.

Figure 14a shows a photograph of Alphonsus taken by the Ranger IX spacecraft. The photograph was taken about 137 seconds prior to impact at an altitude of 322 kilometers above the surface. Distances corresponding to the edges of the picture vary from 120 to 162 kilometers. The elevation of the sun was approximately 10°.

Site 21 BRIGHT TRIANGULAR PLATEAU NORTH OF BILLY (Figure 15)

The surface is hilly with steep slope to the northeast and northwest. The floor of Billy is unusually dark material. To the east northeast there is an eroded crater; both craters are noticeably distorted.

Site 22 SOUTH WALL OF GASSENDI (Figure 16)

This site may permit easy access into Gassendi. The interior of Gassendi has a great variety of features, among them being a central group of mountains, summit craters, a system of clefts, mounds, ridges, and the remains of an inner ring concentric with the eastern wall. Noteworthy is the apparent flooding through a breach in the southeastern wall and the younger impact crater on the surface of the flow.

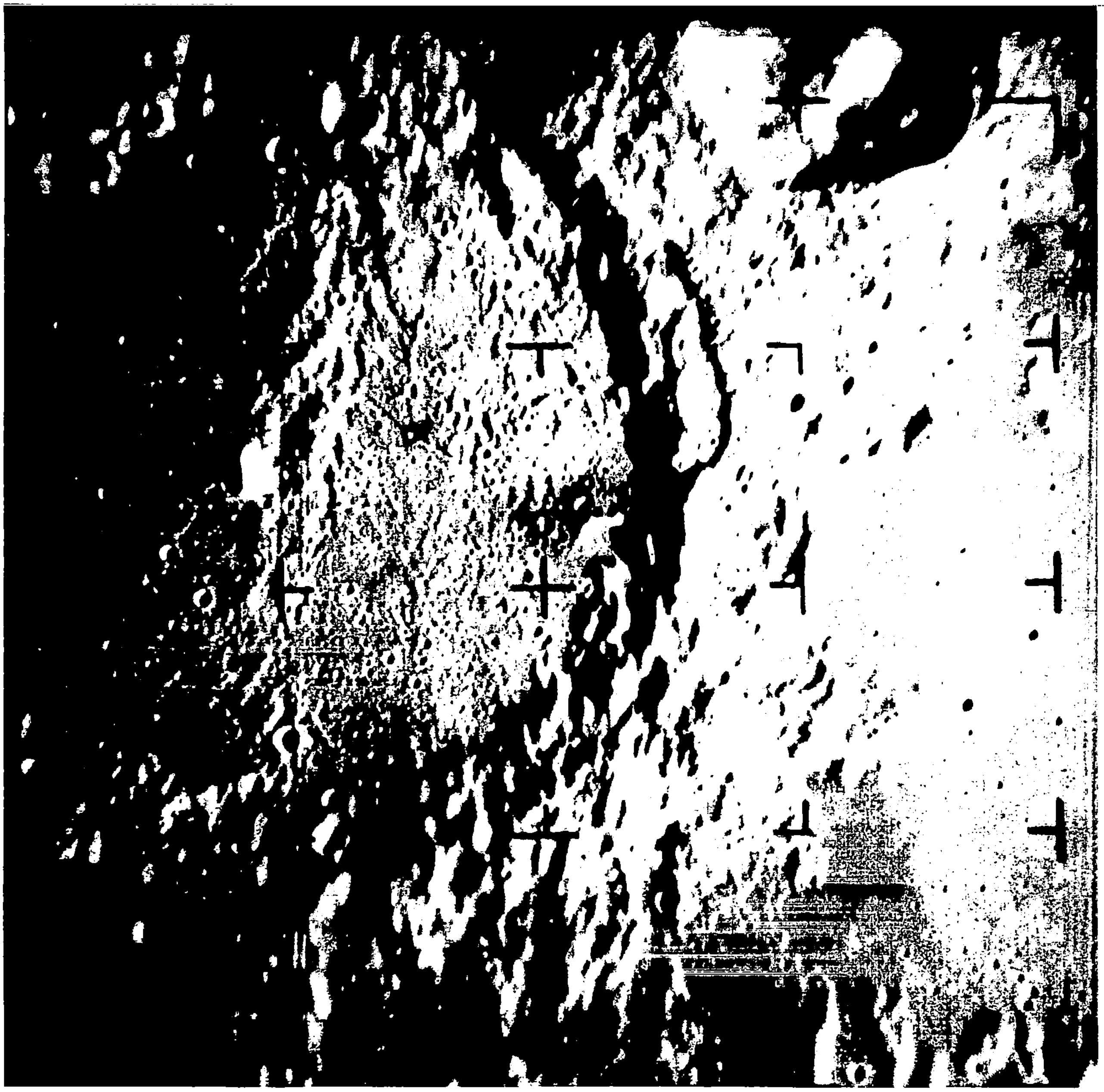

FIGURE 14a. RANGER IX PHOTOGRAPH OF ALPHONSUS CRATER

FIGURE 15. BRIGHT PLATEAU NEAR BILLY

FIGURE 16. MARE HUMORIUM

Site 23 EAST OF LIEBIG IN MARE HUMORUM (Figure 16)

The scarp running along the eastern edge of Mare Humorum is of especial interest in that it truncates a number of craters, suggesting a volcanic feature. In the uplands to the southeast there is an apparent lava bed with evidence of faulting; to the west are great scarps.

Site 24 NORTH FLANK OF TYCHO (Figure 17)

Tycho's great system of bright rays are the most pronounced ray pattern on the moon. The crater, one of the most recent of the large craters, has been considered as a possible source of tektites. The high part of the outer slope is darker than the rays and the interior; inside this dark ring, just outside the crest of the northern rim, there is more bright material. Tycho's dark ring is an excellent example of a feature common to many ray craters.

Site 25 FLOOR OF WARGENTIN (Figure 18)

Wargentin is a quite unusual crater, in that by virtue of its being filled to the lowest point on its rim, it could more accurately be referred to as a hump or a walled circular plateau rather than as a crater. Surface material may be Apenninian. The site is 12 km from a 3-1/2 km diameter crater whose rim may contain fragments of the geological unit responsible for filling up Wargentin.

All of the sites discussed thus far have been nonpolar sites. However, it is possible that some of the most interesting areas on the Moon are at the poles. The reasons for the neglect of polar areas are:

1. Since polar areas can be seen from the earth in only oblique perspectives, one knows even less about polar topography than about areas well oriented for observation through terrestrial instruments. All else being equal, one tends to progress in his exploration plans from the better-known to the less-known.

2. Polar sites impose a propulsion penalty; but this additional fuel requirement is very slight. This penalty should not be held a serious factor recommending against polar landings.

3. The celestial mechanical considerations bearing on polar versus nonpolar operations essentially involve just how frequently one wants to be able to return to the earth, and where one wishes to make changes of his orbital plane - i. e., on the ascent to lunar orbit, or after achieving lunar orbit. The plane of

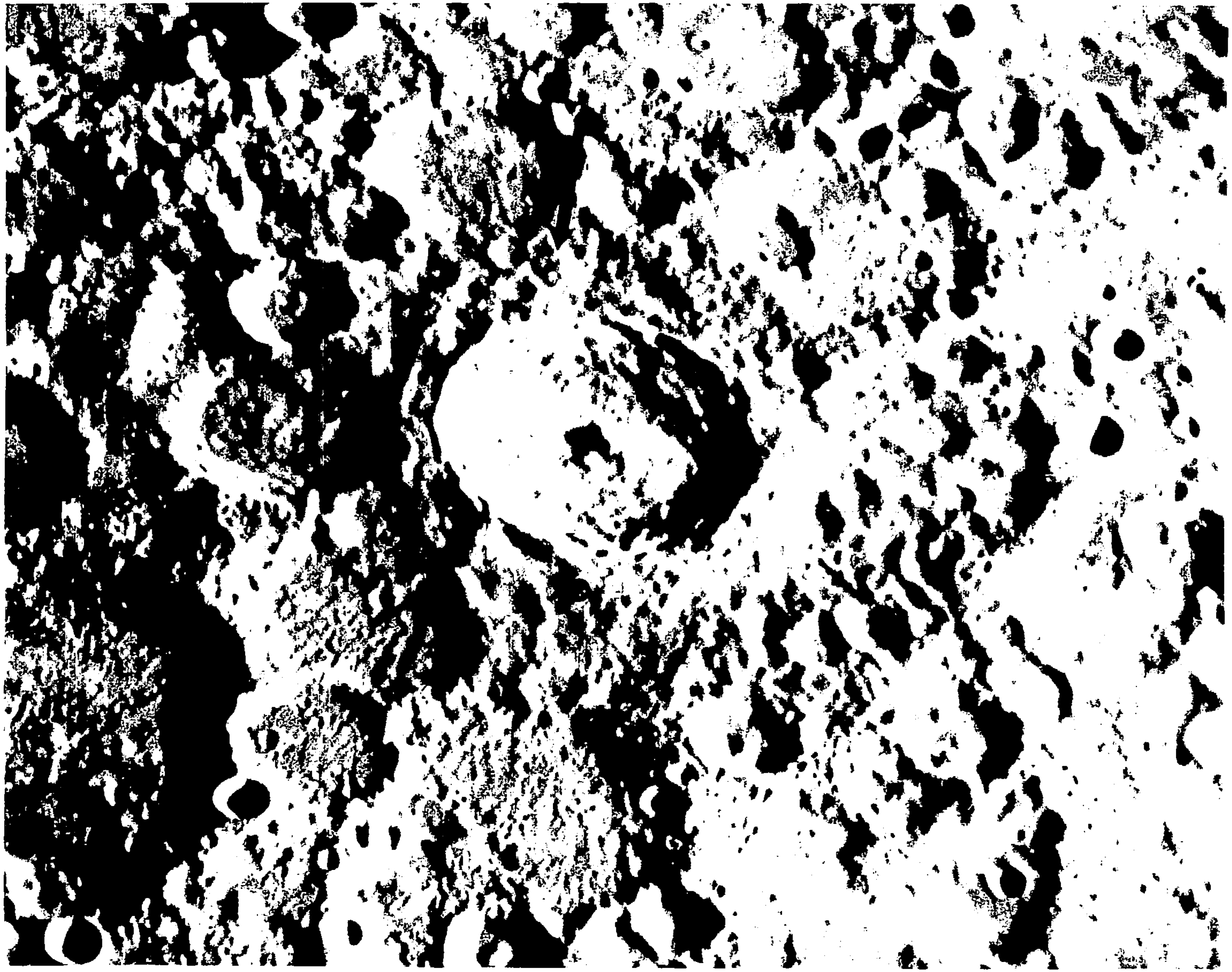

FIGURE 17. TYCHO

FIGURE 18. WARGENTIN

an equatorial lunar orbit very nearly contains the earth at all times; therefore, should an equatorial orbit be used as a parking orbit for a Command Module*, return to the earth would require only a very slight plane change. Furthermore, for a strictly equatorial site the Command Module would pass overhead once every two hours; that is, return to the earth could be initiated every two hours. For sites not on the lunar equator but close to it - e. g., within ten degrees lunar latitude of the equator - an equatorial parking orbit for the Command Module could still be employed; however, the Lunar Excursion Module (LEM) would have to perform a plane change to effect rendezvous with the Command Module. For sites whose latitudes exceed ten degrees, the LEM as presently designed does not have sufficient capability to make all the associated plane changes required if one insists on being able to rendezvous with the Command Module every two hours. In the mid-range of latitude the situation is worse due to the progression or regression of the line of nodes of the parking orbit, which is assumed to originally contain the landing site. This is approximately eleven or fifteen degrees of longitude** a day depending upon whether the motion is progressive or regressive respectively. The result is that after a period of a few earth days, the Command Module passes nowhere near the site, and will not be overhead again until some twelve to seventeen days after the landing. As the latitude approaches 90 degrees (i. e., a polar site) the plane of the parking orbit comes nearer the site; and for a site on one of the poles, the Command Module again passes overhead every two hours. The disadvantage of a polar site in these respects is that the plane of the Command Module's parking orbit, although easily achieved, does not always contain the earth. Thus, although orbital rendezvous might be effected within any two hour period, one would have to effect a plane change after rendezvous, or else wait perhaps as long as a week until the earth is again within the plane of the parking orbit. In so far as the rendezvous and return to earth operation is concerned, an equatorial site is clearly the most advantageous; however, in regard to these considerations for a mid-latitude site versus a polar site, the former is not necessarily favored over the latter.

Then too there are some distinct advantages of a polar site. Not only would the Command Module pass overhead every two hours, but surface temperature fluctuations are far less in the polar areas, and indeed might be eliminated altogether. A surface at the poles oriented at a given angle relative to the sun, would for the same time of irradiation get just as hot as a similar surface on the equator if radiation from adjacent surfaces could be neglected; however, at the poles the solar radiation generally just grazes the surface. Furthermore, areas in the vicinity of the poles whose altitudes are in excess of about 700 meters experience eternal sunshine. Eternal light would be a highly desirable feature for

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* The vehicle which orbits the moon during Apollo expeditions as now planned. The Command Module moreover is the only vehicle of the Apollo complex which returns to the earth.

** Regression and progression rates are also functions of the latitude.

permanent bases in that continuous solar energy would be available not only for power, but also for photosynthetic regenerative life support systems. Finally, at the poles there are areas of eternal night in close proximity to areas of eternal light. These areas of perpetual shade probably have the lowest temperatures on the moon; it is here that one could reasonably expect deposition of minerals by condensation. Some materials which might be "cold trapped" by the dark interiors of polar craters are water, sulfur, ammonium chloride, mercury, and bromine; elsewhere on the moon during the day, these would be readily volatilized. Once these materials were deposited in an area of permanent shadow, where the highest temperatures may be less than 120°K, they would remain for a long time due to extremely slow sublimation rates at low temperatures. Thus contiguous areas of eternal night and eternal day may offer a great technological advantage for advanced lunar projects, providing continuous power and sunshine plus easily available raw materials.

In the polar regions we display the sites discussed below.

Site 26 THE CRATER NEWTON, SOUTH POLE (Figure 19)

The site lies within Newton. Here due to the highly oblique projection, the arrow does not correspond to 35 kilometers. Portions of Newton and the nearby craters are areas of eternal darkness. The walls of Newton, being approximately 9000 meters above the plain, are comparable to Mt. Everest.

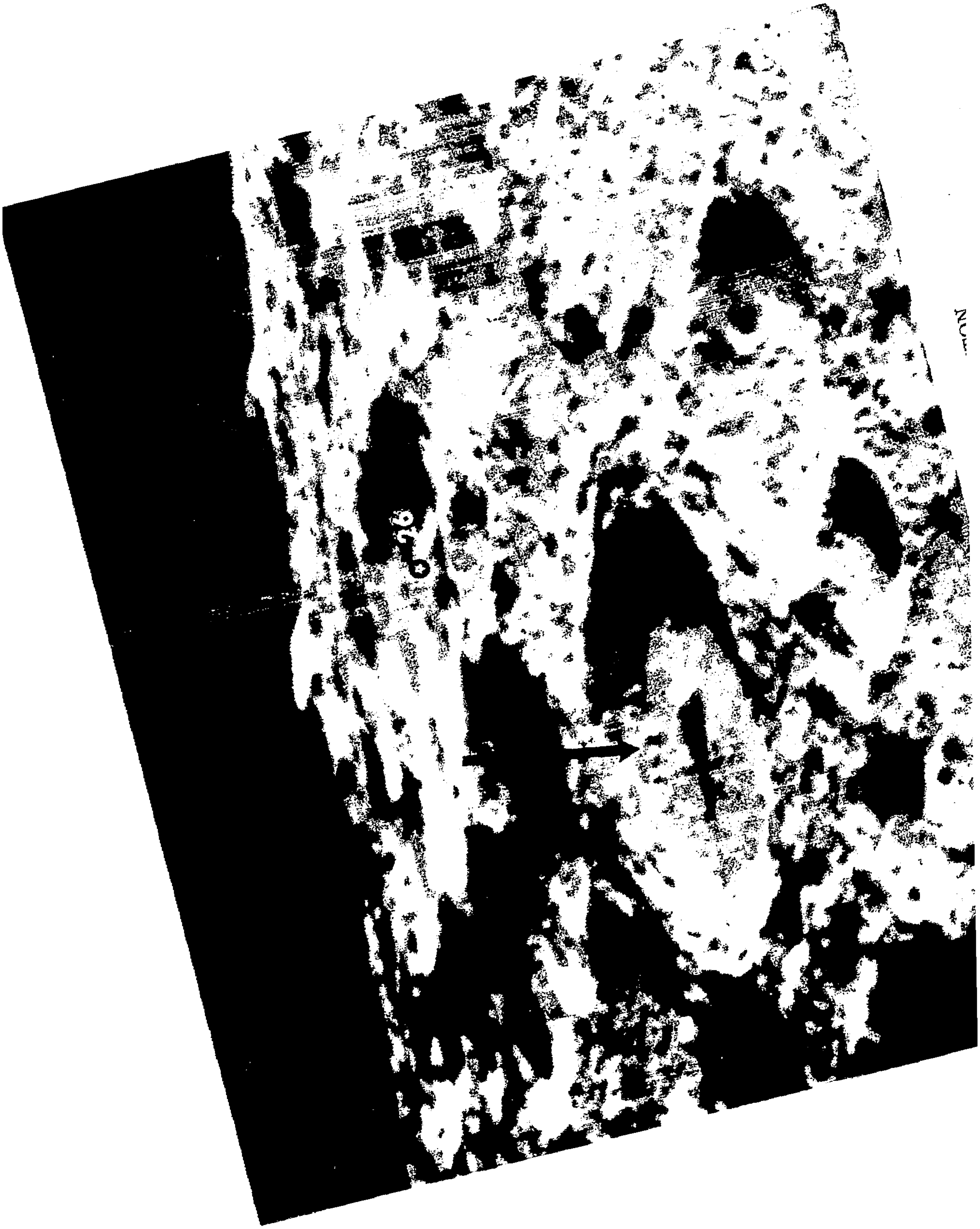
Site 27 THE LEIBNITZ MOUNTAINS, SOUTH POLE (Figure 20) (indicated by triangles)

The same considerations apply to this area as for the Newton area. As is true for all of the polar areas, oblique projection prevents any knowledge of the topography comparable to that available for the lower latitudes. The Leibnitz mountains with peaks of approximately 10,000 meters should afford spectacular topography.

Site 28 THE SHACKLETON MOUNTAINS AND CRATER, NORTH POLE (Figure 21)

These mountains named for the famed south polar explorer may well have areas of continuous light contiguous to or near to areas of eternal night. The pole itself lies within the crater Shackleton. Although this site apparently does not have any other special features, it is typical of far northern sites.

In conclusion, while this survey of lunar exploration areas could hardly qualify as an exhaustive treatise on lunar physical geography, enough material has been presented to establish that there is no unique set of areas to be visited sequentially in a developing program of exploration. Possibly as many different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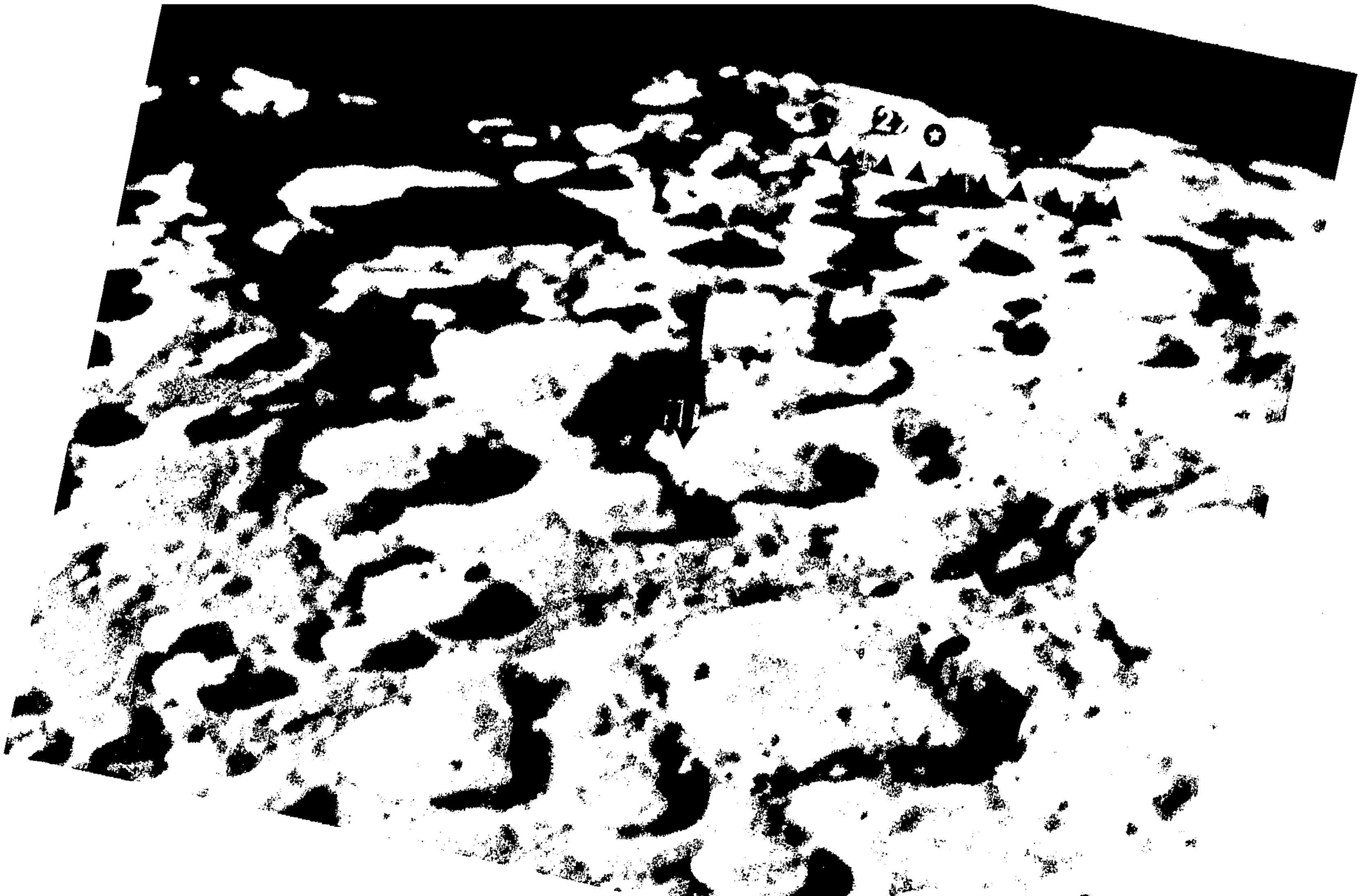

FIGURE 20. LEIBNITZ MOUNTAINS

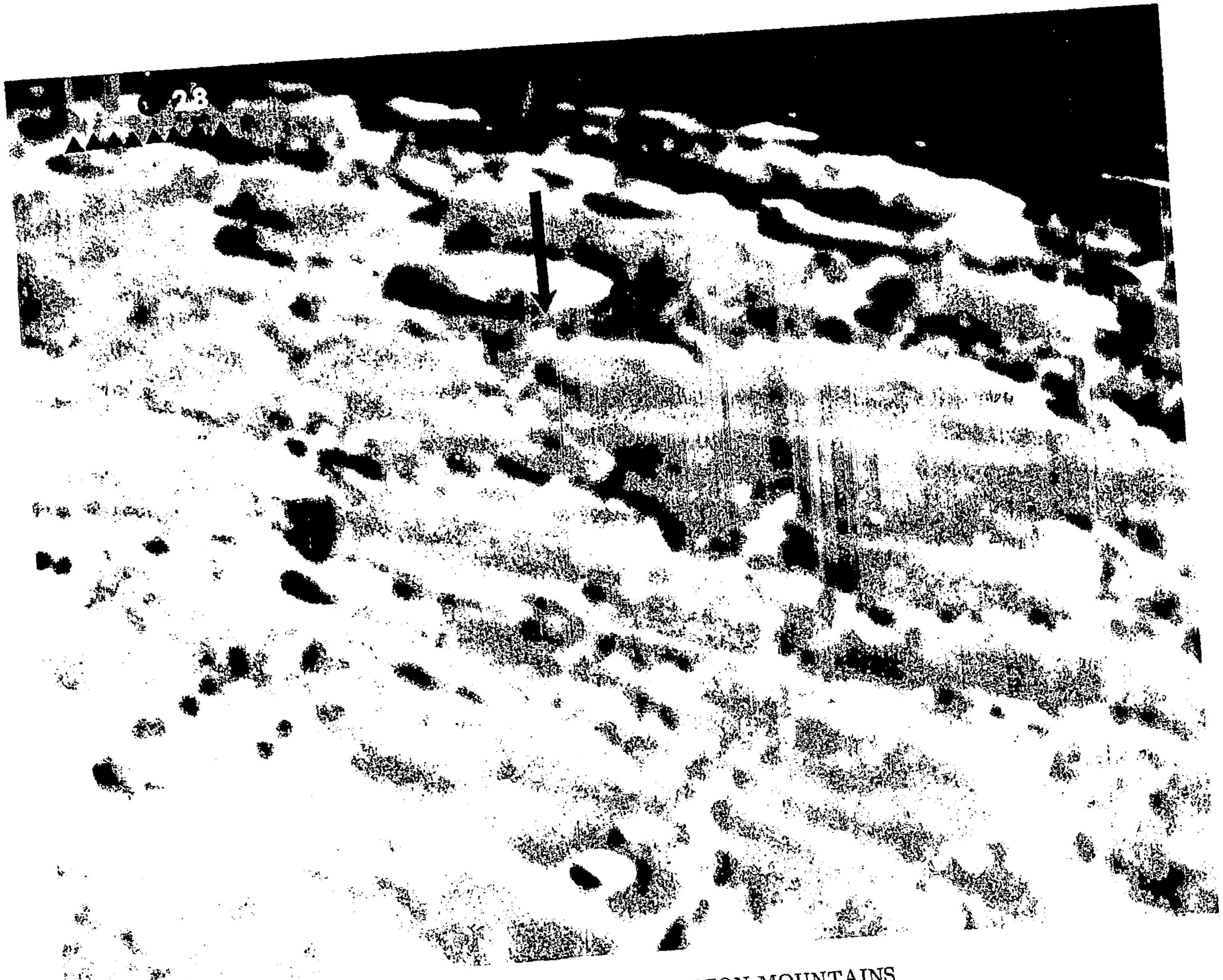

FIGURE 21. THE SHACKLETON MOUNTAINS

programs will be proposed as there are experts. One can expect, though, that any program will generally proceed by working from the relatively well-known to the unknown, taking steps to a degree more arbitrary than usually realized, which balance the desire for new knowledge and experience against the resources for coping with the associated unknown hazards.

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Chapter 3

ENVIRONMENTAL CONTROL FOR EARLY LUNAR MISSIONS

By

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James A. Downey III*

SUMMARY

This paper describes various techniques that may be used to provide early lunar explorers with a life sustaining environment. Specific techniques for accomplishing any given function were selected and integrated into a conceptual environmental and thermal control system. This selection was based upon an early anticipated mission, a specific crew size, an assumed power source, a lunar roving vehicle concept and various other selected performance figures. With these assumptions the authors have arrived at an environmental control system concept. Because of the wide latitude of assumptions possible and of the many unknowns associated with a first generation lunar roving vehicle, this concept represents one of many realistic approaches which could be taken to provide the desired environment. To define the actual system will require an evolutionary trade-off process in which various vehicle subsystems are made to complement each other. From such an integrated approach the optimum environmental control system in terms of current technological capability, weight, size and performance will evolve.

INTRODUCTION

This paper outlines various current engineering methods available for meeting man's life supporting needs for a short lunar mission. The environmental control and life support systems described herein may not provide the crew with an optimum environment in terms of both physiological and psychological needs; however, the systems will provide the necessities for sustaining life. As experience is gained in sustaining life in space, bio-scientists will be in a position to closely define man's biological demands, which will then permit establishing man's environmental limits and tolerances as a function of time. With such specific information, together with evolutionary improvements in equipment and technologies, hardware systems of an optimum nature will be obtainable.

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Previous papers have shown that the moon will present a very harsh and inhospitable environment. First, the moon has no appreciable atmosphere. The vacuum condition of the lunar surface may equal or even exceed the best vacuum conditions that have been produced in laboratories on earth. Second, the thermal environment is extreme. The surface temperatures in lunar equatorial regions vary from about 390° K (245° F) during the lunar day to between 105 and 120° K (-270 to -245° F) at lunar night. Third, the moon has a weak magnetic field that has been estimated to be less than 6×10^{-4} gauss as compared to .5 gauss for the field at the earth's surface. The earth's magnetic field and atmosphere protect life on earth from bombardment by charged cosmic particles. No such processes will be operative in the lunar environment; there will be no natural magnetic shielding for the astronaut on the moon. All cosmic and solar charged particles, except perhaps particles of extremely low energy, will reach the moon's surface. Fourth, meteoroids will impact on the moon since there is no atmosphere to attenuate and consume incoming primary meteoric particles. Secondary meteoroids ejected from lunar material as a result of the impacting primaries may constitute a further hazard to equipment and personnel located on the lunar surface. Fifth, solar ultraviolet radiation and more energetic electromagnetic radiations will also be incident on the lunar surface. Here on earth ultraviolet radiation is attenuated by the upper atmosphere.

In this paper we will be concerned with a system for providing man on the lunar surface with a proper thermal environment, a breathable and nontoxic atmosphere, and food and water. Radiation shielding is not considered in the following discussion. In order to provide man on the lunar surface with a life-sustaining environment, a system capable of providing the environment must be developed. This package of components and subsystems is generally referred to as an "environmental control system".

AN OPEN ENVIRONMENTAL CONTROL SYSTEM

A typical environmental control system must be made up of components which will provide extremely good reliability over the intended space mission. Without this, any manned mission would unduly risk the life of the astronauts as well as the success of the mission. The most logical approach to obtain high system reliability is to develop a simplified system concept with duplication of the most critical components. A first generation lunar mission will have a distinct advantage in this particular area over previous orbital missions. For this mission, components of the environmental control system generally can be selected from those which have previously demonstrated high reliability rather than from those that only show potential.

First, this paper will consider a minimal environmental control system for background. This minimum system will then be evolved in an orderly manner by the addition of various subsystems to obtain the necessary environmental conditions to support a specific manned lunar mission. The assumed mission is a hypothetical one in which two men will be housed in a small lunar roving vehicle for periods up to two weeks. The various systems of increasing complexity which are considered do not necessarily include optimum subsystems, but indicate either a specific technique to accomplish an additional function or another method to accomplish the same function in a better fashion.

A very basic atmosphere supply system is shown in Figure 1. This is categorized as an open cycle system and would be an optimum system for missions of only hours in duration. The necessary atmosphere to sustain human life is supplied by stored, high pressure oxygen. This technique of employing oxygen stored under high pressures was utilized by Project Mercury. Approximately 3.5 kg (8 lbm) of oxygen under 5 X 10^7 newtons/m^2 (7500 psi) pressure was provided for the early missions. This pressure has been found to be optimum from both the gross weight and volume standpoint if equal importance is given to the total system's weight and volume. Within an inhabited enclosure, water vapor is produced by respiration and perspiration from the crew members. Without its removal, the humidity of the cabin or suit atmosphere would increase to the

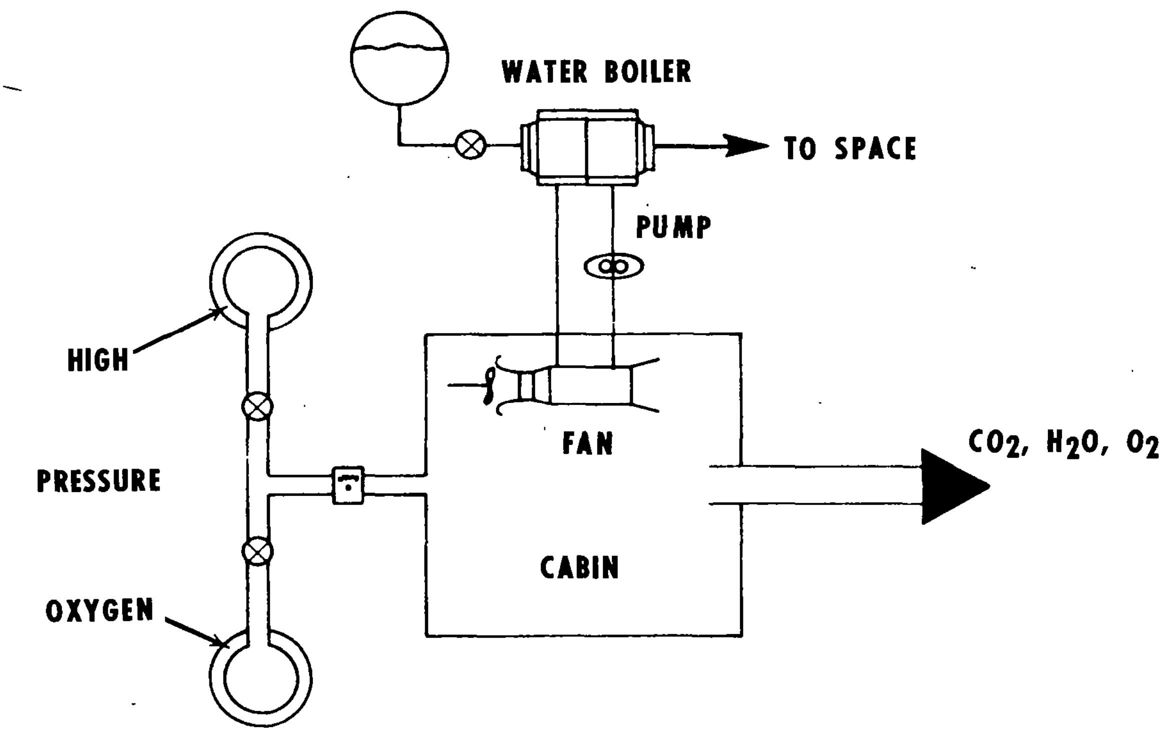

FIGURE 1. BASIC OPEN ENVIRONMENTAL CONTROL SYSTEM

point that the crew would become uncomfortable and their functions would be impaired. Although humid atmosphere is not extremely critical in respect to crew survival, the production of CO_2 brought about by the normal respiratory function will produce a toxic atmosphere if proper control is not accomplished. Generally it is desirable to maintain the CO_2 partial pressure below about 5.5×10^2 newtons/m^2 (4 mm of Hg) if a person is to be exposed to the atmosphere for an extended period of time. Concentration as high as 1.6×10^3 newtons/m^2 (12 mm of Hg) can be endured for short periods. In this basic open cycle environmental control system CO_2, H_2O vapor and trace contaminant concentrations are maintained within comfort zones by controlling leakage from the cabin. That is, a sufficient amount of excess oxygen is supplied to carry overboard any unwanted contaminants. However, in this system unused oxygen is lost overboard with the contaminants. Such an approach to contaminant control becomes extremely expensive in terms of oxygen or atmosphere loss as mission lengths increase beyond a few hours. As an example consider a pure oxygen atmosphere of 3.5×10^4 newton/m^2 (260 mm of Hg or 5 psi) pressure with an allowable CO_2 concentration of 1 per cent and a 2 per cent water vapor concentration . The cabin leakage rate would have to be 100 kg (220 lbm) per man-day based upon the limit established for the H_2O vapor content. If one increases the allowable H_2O vapor content, then the leak rate can be reduced to 75 kg (165 lbm) per man-day without exceeding the allowable CO_2 concentration. This still amounts to nearly 80 times the oxygen flow required for a man's normal respiratory needs.

To control the temperature within the cabin, a water evaporator is used. This unit is simply what its name implies - a heat sink operating on the principle of evaporative cooling. A heat exchanger is employed, one side of which is in contact with the thermal transport fluid, the other with the water evaporant. The latent heat of vaporization of the water is utilized to maintain a heat sink. The actual sink temperature is determined by the back pressure maintained in the boiler. However, to expend an evaporant such as water for complete environmental cooling is in itself expensive from the mass utilization standpoint.

Using this simple open system as a background, a system suitable for a two-week lunar mission will be developed.

A SEMI-CLOSED ENVIRONMENTAL CONTROL SYSTEM

Water Regulation

First of all there exist better techniques than controlled leakage by which one can regulate the concentrations of CO_2 and water vapor. These are illustrated in the system shown in Figure 2. In this system leakage is minimized and unlike the previous case, is undesirable. Contaminants such as H_2O vapor and CO_2 are removed by physical and chemical processes. Water vapor may be removed from the cabin or suit circuit by either chemical means or by heat exchangers operating at the desired atmospheric dew point. Chemical absorbents of water vapor such as calcium chloride and barium oxide are not desirable for long periods of space application. They must be regenerable if they are to be satisfactory from a weight standpoint and in order to regenerate the beds an extremely high temperature source of about 500°K (440°F) must be available. In addition considerable amounts of energy are required to regenerate a hydrated absorbent. Thermal energy equal to the heats of reaction and condensation must be supplied. To consider the process from the reverse standpoint, during the desiccant's absorbing cycle an exothermic reaction occurs in which both the unwanted heat of the reaction and the latent heat of H_2O condensation is liberated. This heat is dumped into the air circuit and must then be removed by the vehicle's thermal control system. Chemical adsorption of H_2O by a material such as silica gel is a more appealing approach. This operation relies upon surface attraction between the water molecules and those of the adsorbent rather than upon chemical reaction, as in the previous case. Therefore, the thermal energy required for desorption of an adsorptive bed is less and amounts essentially to the latent heat of condensation. In addition the thermal energy can be supplied at relatively low temperatures of about 390°K (245°F). The use of a nonregenerable solid adsorber such as silica gel could find application for cabin humidity control for extremely short missions. However, silica gel consumption is directly proportional to the

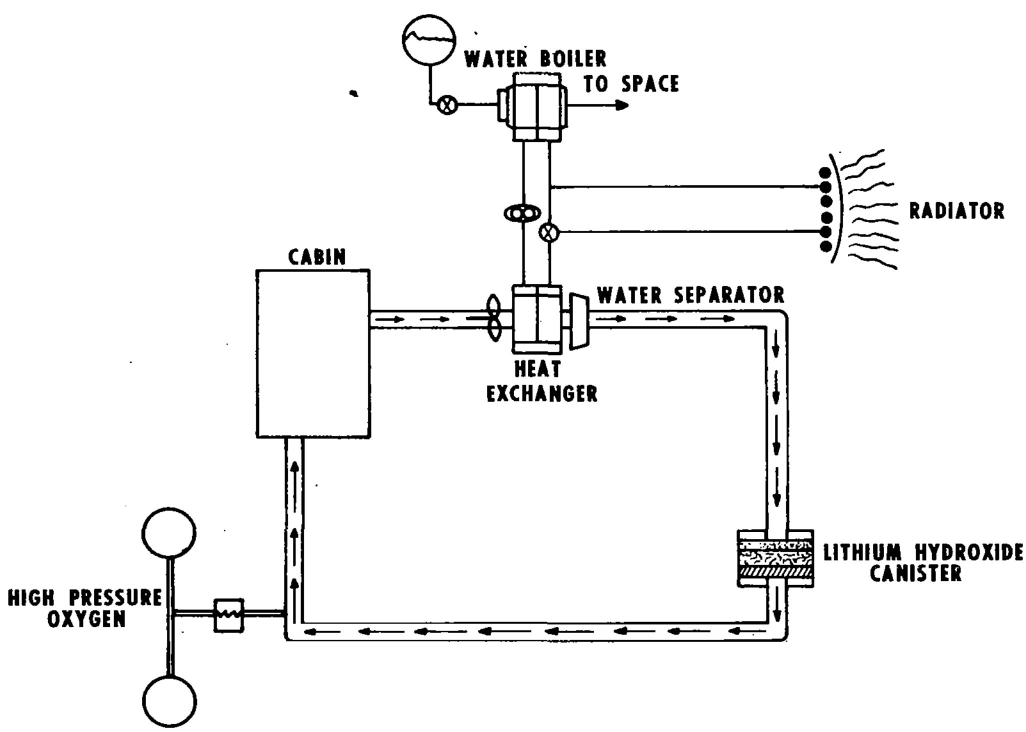

FIGURE 2. SEMI-CLOSED ENVIRONMENTAL CONTROL SYSTEM

mission length and therefore becomes prohibitive for long missions. Making such a system regenerable increases this period of usefulness. However, since water is lost during the regeneration process there is a weight penalty involved with the use of even the regenerable system. In addition, the surface of the adsorbents deactivates upon repeated generation with heat. This particular method of humidity control finds its best application in systems requiring relatively low mass flows. It is therefore normally utilized in conjunction with the CO_2 management system in which only a portion of the air is cycled through the adsorbent bed. This will be described in detail below.

The humidity control approach shown in Figure 2 is the one which is considered to be the simplest and most effective. The air stream is cooled and moisture condensed out by passing over the coils of a heat exchanger. Within the airstream a liquid water separator is placed to prevent water droplets from being carried in the airstream. A water separator is considered by many as an item needed only in an orbiting space vehicle's environmental control system to facilitate water removal under null gravity conditions. However, in addition to this application, water separators are required when heat exchangers and evaporators are designed for minimum volume. In such instances, in order to obtain the desired air flow, the air velocity through the compact units must be high, and suspended water droplets may then be transported within the airstream. The simplest water separator consists of a sponge system in which water is trapped. To regenerate the sponge a mechanical actuator is employed to squeeze it. This technique was utilized in the Mercury capsules.

Carbon Dioxide Removal

As was indicated previously, CO_2 removal and disposal by controlling cabin leakage is extremely costly and therefore unrealistic, except for very short missions. The next step up the ladder in CO_2 removal techniques is the use of chemical absorbers. Metal hydroxides and superoxides can be utilized for this purpose. One of the best known commonly used chemical absorbers is lithium hydroxide (LiOH) which, besides being used on naval submarines, has been successfully employed in the environmental control system of the Mercury vehicle. In operation, the cabin air is passed over a bed of LiOH granules. The CO_2 constituent of the airstream reacts chemically with the LiOH to form lithium carbonate and water vapor. The LiOH beds cannot be readily regenerated and therefore have a steep linear weight penalty associated with mission duration. However, the current state-of-the-art has progressed to the point that extremely good utilization of these canisters can be achieved. In the theoretical chemical reaction, approximately 1.1 kg of LiOH would be required for each kilogram of CO_2 removed from the atmosphere. Experiments by the Garrett Corporation indicate that canisters can be built that will require only 1.15 kilograms of LiOH for each kilogram of

CO_2 removed. With such a high utilization, (nearly 95 per cent), only slightly more than a kilogram of LiOH per man-day is required for CO_2 management. This is not an extreme penalty and various trade-off analyses indicate that such an approach is quite economical for missions of up to 10-14 days.

Metallic superoxides have been suggested for absorbing carbon dioxide during space missions. Sodium and potassium superoxides are substances that have been used in demand type breathing systems. They absorb the exhaled carbon dioxide and at the same time liberate oxygen approximately equal to the amount required for respiration. However, these materials are highly reactive and therefore represent a handling hazard. Control of the reaction rate and subsequent matching with the crew's metabolic requirements represent problems since performance is dependent upon air flow rates, humidity, and temperature as well as bed sizing and construction. An adequate superoxide system would seem to require an extremely complex regulatory system, especially for a spacesuited astronaut.

Temperature Control

Thermal control is accomplished by an integrated water evaporator and space radiator. One may ask: Why not use only a radiator? In reply, there are problems associated with thermal control systems dependent only upon the radiative process for heat rejection. All functional subsystems will emit excess heat that must be rejected or stored in some manner. However, the problem is that these various heat sources do not emit this thermal energy at the same temperatures. For example, the power system and some electronic equipment will dissipate heat at relatively high temperatures. Such thermal sources are adaptable to radiative transfer; thus thermal control can be realistically accomplished by radiative processes. However, if additional thermal energy must be rejected at low temperatures, such as are necessitated by man's requirements and for humidity control, space radiators become unrealistically large. This is due to the fourth power relationship between net radiative power and absolute temperature. Therefore, a combined system is used in which the radiator is used for cooling at higher temperatures and a water evaporator for cooling at the lower temperatures.

Mission Duration Limits

All the basic subsystems that will perform the functions of thermal control, supply of atmospheric constituents, CO_2 and humidity management are indicated in the system shown in Figure 2. However, from mass considerations, such a system would be desirable for missions of only two or three days duration. Note that a quantity of water is lost to space through the evaporative heat exchanger, that LiOH consumption increases directly with mission time, and that oxygen for atmospheric supply is stored in a gaseous state. These considerations limit the mission duration of this type of system.

A TWO-WEEK ENVIRONMENTAL CONTROL SYSTEM

Figure 3 shows an environmental control system which might be suitable for a two-week mission in either a lunar shelter or roving vehicle. First consider the selection of the cabin environment. There has been a controversy concerning the merits of pure oxygen systems versus systems incorporating oxygen-nitrogen environments. There are various reports of physiological complications resulting from prolonged exposure to pure oxygen. Anemia and degradation of lung tissue are mentioned. The argument seems to revolve around the question: How much time on 100 per cent oxygen is too long? Various sources contend that for missions of two weeks to a month no significant effects will result from continuous exposure to pure oxygen. Gemini and Apollo environmental control systems will be 100 per cent oxygen. Other authorities, however, express some concern for exposures to pure O_2 for periods of only a week. In addition to the possible physiological complications, another disadvantage of the 100 per cent O_2 system is the fire hazard problem. The disadvantages of O_2 - N_2 systems are higher leakage rates at the higher total pressures, increased system weight and complexity, requirements for reliable partial pressure sensors, and dangers

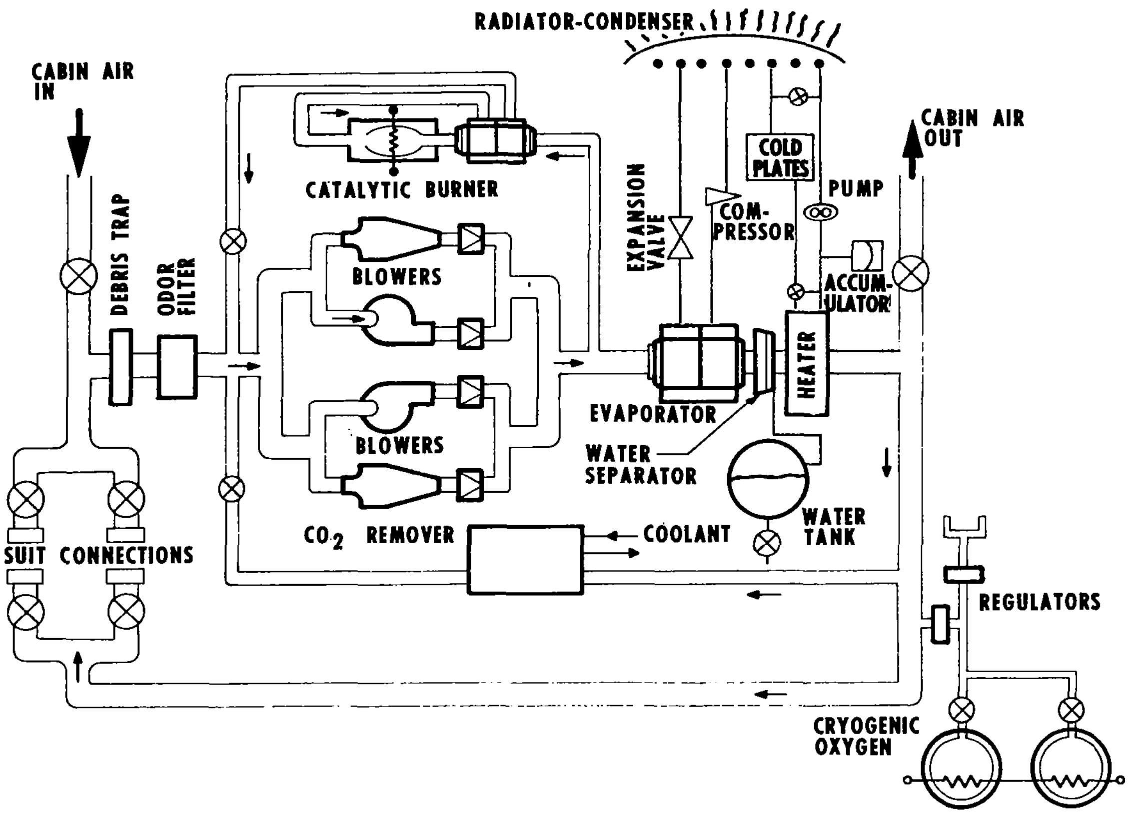

FIGURE 3. LRV ENVIRONMENTAL CONTROL SYSTEM

of experiencing the bends while transferring from a mixed gas environment to a spacesuit system on 100 per cent O_2 with attendant operational problems. However, for the purpose of this paper, this highly controversial subject will not be discussed. Apparently some very carefully controlled experiments covering a wide range of concentrations and total pressures must be conducted before the pure O_2 versus two-gas system controversy is resolved. For the sake of simplicity, and compatibility with current programs, a pure oxygen environment has been selected for the system for the two-week lunar mission discussed below.

Atmospheric Constituent Supply

The environmental control system forms a closed loop which encompasses both the cabin and the astronauts' pressure suits. The oxygen necessary for cabin pressurization and respiration is supplied by cryogenically stored oxygen. This differs from the basic system previously discussed in which the O_2 was supplied from a high pressure gas source. Cryogenic storage for relatively large quantities of oxygen possesses such advantages as greater density storage, reduced container weight, and reduced storage pressure with an inherent increase in safety. The cryogenic fluid also provides a potential low temperature heat sink that can be utilized by the thermal control subsystem. Fluid expulsion from these tanks occurs by pressure developed by heating of the stored fluid. Depending upon the desired use rate, the thermal energy can come from either heat leakage through the container wall and structure (if sufficient) or from an auxiliary heating source. If an extended storage time on the lunar surface prior to usage is expected, say three to six months, studies performed by the Future Studies Branch of the Kennedy Space Center indicate that the subcritical method of O_2 storage is more economical than supercritical storage. The two-phase storage of O_2 in the subcritical condition does not present difficulties for a lunar surface payload because of the presence of a significant gravity field. The problem of phase separation in an orbiting mission under zero gravity conditions generally makes supercritical storage more desirable. Although not shown in Figure 3, the primary power source of a lunar shelter or surface vehicle for a two-week mission will probably be a hydrogen-oxygen fuel cell. Therefore, oxygen will presumably be carried as a reactant for the power system. The oxygen tank vent pressure is set at about 7×10^5 newton/m^2 (100 psi) to be compatible with this type power system. Analysis indicates that an optimum tank structure can be obtained which will provide unvented storage of oxygen during the six-month storage period. Essentially the only cabin controls required for this atmospheric system are a total pressure sensor, on-off valves, pressure reducers and a pressure relief valve in case of tank or control malfunction.

Blower System

To obtain sufficient air flow, a system of fans or compressors is used. Due to mission dependency upon these items, two parallel sets are employed for redundancy reasons with only one set functioning at any given time. Since these blowers will be utilized in a system which will operate at varying pressure heads, their selection is not straightforward. During the period in which the astronauts are within the cabin, the fans will be required to perform at relatively high flow rates but relatively low pressure heads. However, during pure suit operation the fan system will have to operate against a greater head due to the increased pressure drops across the suits. Then, of course, there are various situations when the blowers must operate under different flow and pressure conditions, for example when one astronaut is on the lunar surface. The blower system shown is capable of providing the necessary performance over a range of operating conditions; separate fan-axial compressor units are employed.

Contaminant Removal

A catalytic burner or oxidizer which will remove combustible contaminants from the atmosphere is placed directly across the blower system. Such critical contamination as hydrogen, carbon monoxide, and methane, as well as more complex hydrocarbons, are oxidized and converted into inoffensive and harmless gases. Since the process by which these contaminants are rendered harmless requires thermal energy, two techniques are generally used in an attempt to conserve the burner power requirements. First, as indicated in Figure 3, the atmosphere to be processed is tapped from the main atmospheric control circuit just subsequent to exit from the blower system. By tapping at this location the air is at a relatively high temperature. Second, from this point the air is then passed through a regenerative heat exchanger where regenerative heating is accomplished by the exhaust gases from the burner. Once in the burner, the temperature of the warm air is further increased by electrical heaters prior to passing over the catalytic beds. These beds are usually composed of materials such as Hopculite, platinum or palladium on an asbestos substrate. If the atmosphere is at a sufficient temperature the unwanted impurities will enter into the desired chemical reaction and become oxidized. The minimum temperature required in the burner depends on the gas to be processed. One of the most difficult contaminants to oxidize appears to be methane which requires burner temperatures in the range of 550-650° K (530-710° F). After the impurities have been processed the heated exhaust gases pass through the regenerative heat exchanger and are cooled prior to re-entry into the main airstream. The entire catalytic burner unit is quite small, weighing in the neighborhood of 2 kg and generally requiring from 10 to 20 watts of electrical power. With the unit placed across the main blower system as indicated, operation without a separate blower system is possible.

Temperature and Humidity Control

The next units in the main air circulating circuit are the heat exchangers used to control the temperature of the atmosphere. Equipment to do this job satisfactorily as well as control the humidity of the atmosphere can become quite complex. It may employ water evaporators, coolants, cryogenic heat exchangers, regenerative exchangers, radiators, by-pass circuits, and water separators, in addition to a maze of plumbing networks and control systems. A simple system, from the standpoint of illustration anyway, is a vapor compression cycle such as one might find in commercial air conditioning units. Although there is a question whether or not specific weights of power systems can be made low enough to justify the use of a heat pump from a weight standpoint, there are other factors which merit its consideration. A refrigerant cycle would be desirable for inclusion in any system where the payload configuration restricts the size of radiator panel, where an extremely low effective sink temperature is not available,where precise control may be desired and where greater design range capability may be required because of lack of knowledge of the external thermal radiation characteristics or variable operating conditions anticipated. In the case of a lunar roving vehicle, all these restrictions are evidenced and therefore even though a vapor compressor cycle may increase the weight of the vehicle, it probably will still be desirable from the standpoint of the other derived benefits. The system shown in Figure 3 represents the use of several thermodynamic vapor cycles which might find application. The evaporator, in order to provide for both satisfactory humidity control and reduced fan power, should operate in the neighborhood of 275°K (35°F). Upon leaving the evaporator the refrigerant enters the compressor and is raised to some condenser pressure. Selecting the ultimate condenser pressure and therefore the saturation temperature is not as straightforward as the evaporator temperature choice. There are essentially two competing factors which work against each other in selecting the heat rejection temperature for the cycle. High temperatures in the radiator condenser section are desirable in order to permit the use of small radiators. This factor is very important when considering the small area available for these items on a lunar roving vehicle. However, from a consideration of Carnot cycle efficiency, as the temperature difference between the evaporator and condenser increases, the cycle coefficient of performance decreases. With the lower coefficient of performance, more work is required and the compressor demands greater power. Perhaps this can be better illustrated by an engineering example. Figure 4 shows the power requirements versus radiator area for a vapor compression heat rejection cycle. This figure gives the power-area trade-off for a Freon 11 refrigerant system. If one assumes that the cabin thermal load is 1500 watts (5130 BTU/hr) and that the condenser is operating at a pressure to provide a saturated fluid temperature of 310°K (99°F), a radiator of 19 m^2 (205 ft^2) would be required with a compressor power requirement of 300 watts. However if we increase the radiator temperature to 370°K (206°F) the necessary radiator area would be reduced to only 5 m^2 (54 ft^2), but the power required would be increased to more than a kilowatt.

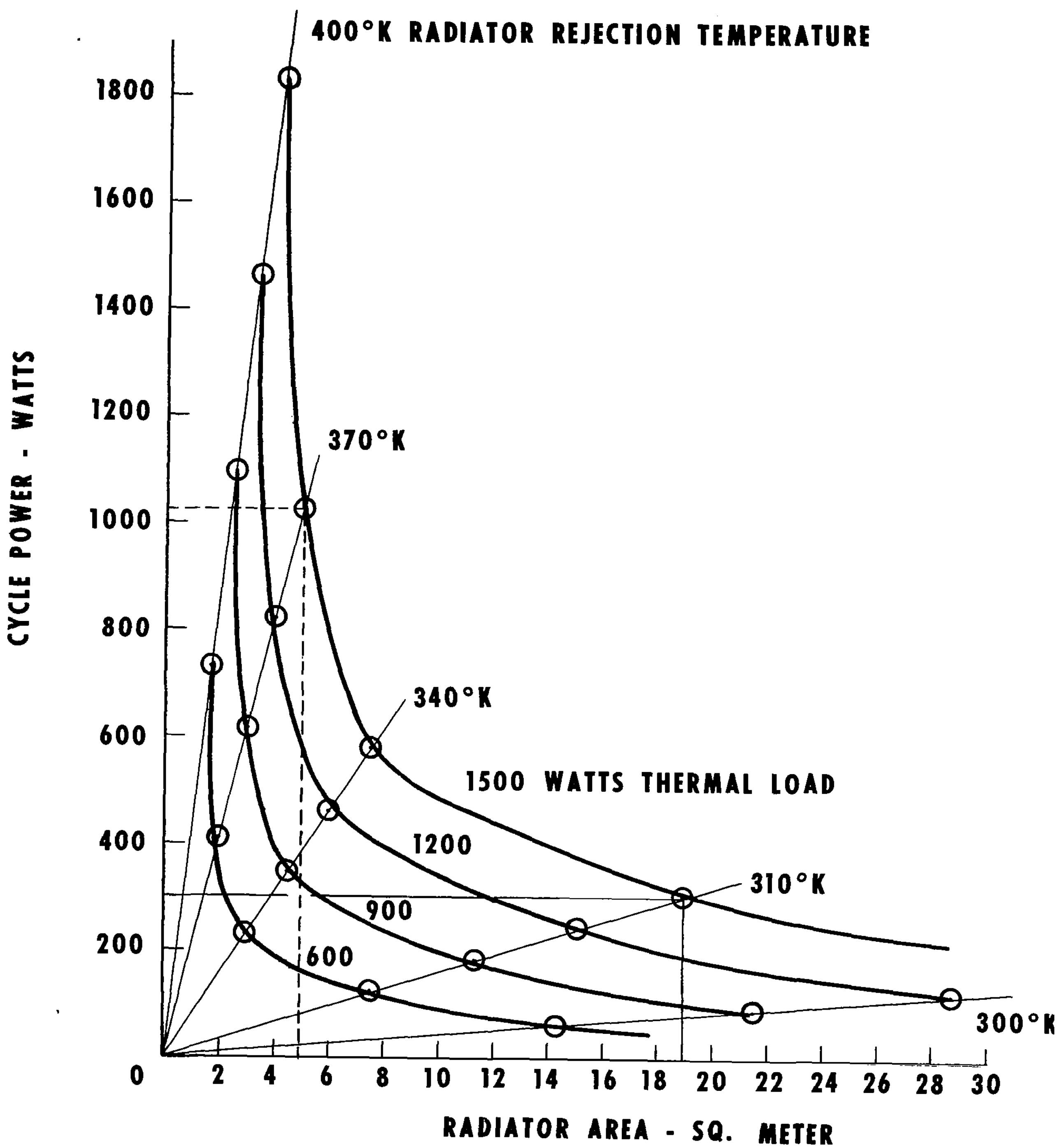

FIGURE 4. FREON-11 VAPOR COMPRESSION CYCLE PERFORMANCE (RADIATOR $\epsilon = .91$; $\alpha = .26$)

When one attempts to control both the humidity and temperature of the airstream with one heat exchanger, problems usually evolve. This generally occurs when the air flow rate through the exchanger (evaporator in this case) is not compatible with both the desired conditions of airstream temperature and humidity level. Therefore a second heat exchanger is shown which adds heat to the airstream. This exchanger, as shown here, is also part of an additional cooling circuit used in conjunction with the electronics. Since these components operate continuously at relatively high temperature the coolant, at temperatures near 340°K (150°F), can be utilized to supply additional thermal energy to the cabin or suit airstream. Although Figure 3 shows this control loop as an apparent entity in itself, in reality this would not be the case. This subsystem would normally be integrated with both the cryogenic and power systems' heat rejection schemes.

In any environmental control system there are numerous approaches which can be used to obtain a desired effect. Thermal control is no exception; Figure 5 shows one of the many possible alternatives to the system just discussed. In the approach taken here, a vapor compression cycle is not used, but water evaporator and cryogenic heat sinks are employed. If one follows the air path, the first heat exchanger could be an air-to-glycol unit in which the sensible heat content of the atmosphere is removed. The exit temperature of the air from this exchanger has not reached the dew point temperature. The exchanger's glycol coolant loop is connected to a space radiator and a water evaporator. Proper thermostatic controls would monitor flow and route the coolant between the radiator and water evaporator to maintain the desired main circuit heat exchanger temperature. The atmospheric gas would then enter a regenerative heat exchanger that would further reduce its temperature. For the present do not consider the function of this unit but follow the atmospheric gas into the third heat exchanger. Here the dew point of the gas is reached and the atmosphere is dehumidified and the latent heat load removed. Some supplemental sensible cooling may occur in the dehumidifying process. The heat exchanger is shown to be cooled by the cryogenic reactant supply. It could also be cooled in a similar manner to the first exchange unit. In such a case a thermal sensor located in the steam side of the evaporator would provide for an evaporator temperature of around 275°K (35°F). An excessive amount of H_2O flow to the evaporator would cause the condensate to freeze in the air side of the exchanger. From this exchanger, the cold and dehumidified air enters the regenerator in the other direction where its temperature is increased before return to either the cabin or pressure suits. By following this air circuit it can be seen that by incorporating the regenerative heat exchanger, moisture can be condensed from the airstream to obtain humidity control as well as to provide air to the cabin or suits at a comfortable temperature. Such a system would be monitored by the use of two by-pass valves, one around the regenerator and the other in the coolant circuit of the first heat exchanger. If one finds that the air is entering the cabin or suit at too high a temperature, the regenerator by-pass will open, thereby providing less reheat. Under conditions which require maximum heating the by-pass valve would remain closed and the air mass would pass entirely through the regenerator. In this manner the atmosphere can be heated without reducing the efficiency of the dehumidifying process.

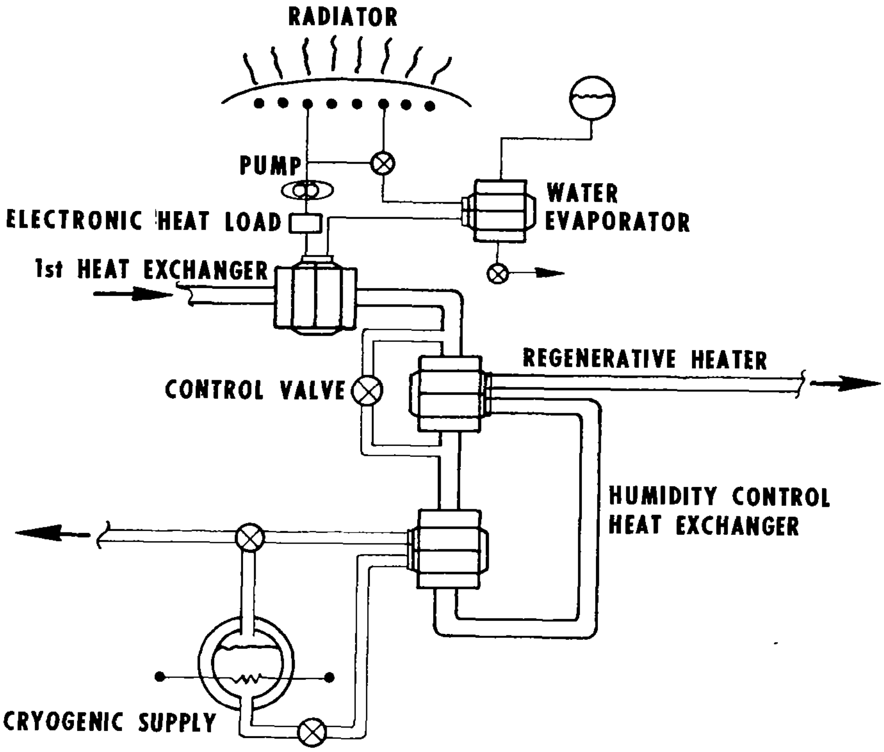

FIGURE 5. ALTERNATE COOLANT LOOP

As one can see, this latter system of thermal control requires an expenditure of water. One should not eliminate this approach from consideration until a detailed system analysis is made. Since there exist numerous methods by which other vehicle subsystems may be integrated with the thermal control system, the water penalty may not be severe. As an example, if oxygen and hydrogen are used for power system reactants, the H_2O by-product of the fuel cell will probably be generated at a rate exceeding the crew requirements and therefore could be economically used within the evaporator. In addition, as previously mentioned, these cryogenics possess an inherent thermal sink which can be utilized in conjunction with other heat sinks.

Radiators

The thermal control systems described above utilize radiators for rejecting either all or some portion of the waste thermal energies. The performance of these radiators will be a function of such parameters as temperature, orientation, surroundings and surface conditions. By examining a heat balance equation written on an elemental area of a radiator it becomes quite obvious that the spectral surface characteristics play a predominant role at relatively low radiator temperatures. At these low temperatures the value of the ratio of solar absorptance (α_S) to infrared emittance (ϵ_T) is very significant in establishing the net heat rejection capability of any radiator. One must provide essentially a solar reflector which consists of a surface with a very low α_S/ϵ_T ratio. Although one may obtain an easily applied surface coating that possesses an initial low α_S/ϵ_T ratio, other factors must be considered. First of all the surface must possess adequate stability for the intended mission. The problem is to provide adequate resistance to solar ultraviolet radiation to prohibit surface degradation resulting in an increase in the solar absorptance value. Even though the spatial environment has very little effect on the infrared emittance value, the increase of the solar absorptance value is sufficient to cause a significant adverse change in the α_S/ϵ_T ratio. However, as the radiating body's temperature increases, the environmental thermal inputs become negligible in comparison to the radiated flux. Therefore, if it is possible to operate a radiant heat rejection device at high temperatures the thermal control system will not be as dependent upon the degradation of spectral selective surfaces. Since for high temperature radiators the thermal emissivity parameter is the predominant factor in determining the net radiative power, one would only have to concentrate on producing a stable coating possessing a high emissivity -- the higher the better. There exist many other problems in addition to obtaining the proper optical characteristics and stability of thermal coatings for space radiators. A few desirable physical properties include: proper thermal expansion match between the coating and substrate, good structural properties, low vapor pressure, low interface resistance and good thermal stability. When used on the lunar surface,a thermal control system that employs a fluid-filled radiator must be designed to prevent freezing. The freezing possibility exists due to the wide fluctuations of thermal inputs between lunar day and night. If the radiator is sized for the peak power operations during the day, then at either low loads or during the lunar night it is possible that the system could freeze. To alleviate such a condition various approaches to the radiator design may be made. A basic approach, and one which is used extensively in passive thermal control systems, is the use of shuttered radiators. The net heat rejected is a function of the amount of exposed radiator. This is analogous to the use of venetian blinds in the home. With the shutters closed the unit would expose a low infrared emitting surface, and conversely with them open a highly emitting surface would be revealed. The greater the exposure, the larger would be the heat rejection capability. By mounting shutters on a fluid-filled radiator the fluid outlet temperature could be held essentially constant by varying the shutter openings whenever the internal load or environmental flux changed. This approach does increase weight and probably could not be employed economically on large radiators. Other control techniques include the use of radiator by-passes, regenerative heat exchangers, integral heaters either to heat the fluid in the radiator or to increase the thermal load artificially, compartmental radiators or undersizing the radiator and using supplemental heat rejection techniques at maximum load conditions.

Referring back to Figure 3, after the process air leaves the dehumidifying heat exchanger, the free water entrained in the airstream must be removed. There are better techniques available for water removal than the absorbing sponge described earlier. The Gemini vehicle uses a more sophisticated approach by employing an integrated cooler-water separator. A wicking material is placed between the plates of the cooler and through capillary action withdraws the water that condenses on the exchanger fins. The water is then piped off to storage. In addition to these two types there are various units available that separate water from the airstream by centrifugal action. These units can be driven in a number of ways; by oxygen boiloff, by electric power, or by the airstream itself. Then from the water separator, the airstream is directed to either the suit or cabin circuit.

Carbon Dioxide Removal

For removing CO_2 from the atmosphere a regenerative molecular sieve is employed. Since this piece of equipment may prove to be the most desirable for missions in the order of two weeks and beyond, a discussion of a typical unit follows. First of all a molecular sieve, sometimes referred to as a microtrap, is essentially a bed of small synthetic zeolite spheres about 2 to 3 mm in diameter. The atmosphere to be processed is passed through a bed of this material with subsequent adsorption of the CO_2 molecules upon the surface of the material. These beds can then be rejuvenated by purging or exposing to vacuum, heat or a combination of the two. Unfortunately the zeolites possess a greater affinity for water vapor than for the CO_2 contaminant. If excessive water vapor is in the atmosphere it must be removed prior to entry into the CO_2 adsorbing beds. Without this removal the bed would become poisoned with H_2O and be of little use in removing CO_2. Therefore, a desiccant is utilized upstream of the sieve. Figure 6 indicates the flow of the airstream through the CO_2 removal system. Since the adsorption capacity of the molecular sieve is greater at low temperatures, the air to be processed is removed at the exit of the heat exchanger or evaporator. This relatively low temperature air is directed into a desiccant bed where it is dehumidified to a low dew point temperature. Although this bed may be either process can be continuous with one set of canisters processing the CO_2 contaminant and the other being regenerated. The system shown utilizes the main circuit compressors to drive the air through the molecular sieve unit. A separator process fan could be placed within the circuit if desired.

One might question the selecting of such an apparently complex and heavy piece of equipment for CO_2 removal when current space vehicles are satisfactorily using lithium hydroxide canisters. The significant factor here is that the regenerable system entails no direct consumption of expendables such as LiOH. For this reason, with increasing mission times the essentially fixed weight unit will become superior to a system whose total weight is directly related to mission length. Based upon current hardware and estimated performance data from the Garrett Corporation, Figure 7 was drawn to provide a weight comparison between the two systems. These data are based upon a two-man lunar mission and assume that any required thermal energy is supplied through electrical resistance heaters. There are two consumption rates indicated for the lithium hydroxide system. The higher consumption rate is not accredited for the water vapor that evolves in the reaction, whereas the lower expendable rate is. It is not easy to say whether or not one should consider water vapor production as a positive factor during a system optimization analysis. If during the mission water is needed, approximately .8 kg of water will be available per day of operation. However, if this water is not needed, it should not realistically be considered as a system asset. Since the lunar roving vehicle's main power system is assumed to be a water producing fuel cell and since its average power level will be such that excess water is produced, the larger weight penalty should probably be used for the assumed mission. The time when the molecular sieve system becomes more desirable from a weight standpoint occurs at about 8 days of operation. By no means is this time exact or as a matter of fact is it the only consideration. The system selection is not straightforward since the point at which the molecular sieve system begins to show definite advantages is near the length of our selected two-week lunar mission. The exact crossover point will be a function of the degree to which the regenerable system can be integrated with the vehicle's other subsystems and the allowable CO_2 partial pressure. The regenerable system's fixed weight as well as its specific reactant consumption will decrease as the CO_2 partial pressure limit is increased. The lithium hydroxide method should also be considered in light of its proven performance and simplicity. A lithium hydroxide canister might well be used as a back-up system to the first generation regenerable CO_2 removal system.

Weight Estimates

Estimating a system weight for any hypothetical lunar payload such as the ECS system of a lunar roving vehicle is quite difficult for various reasons.

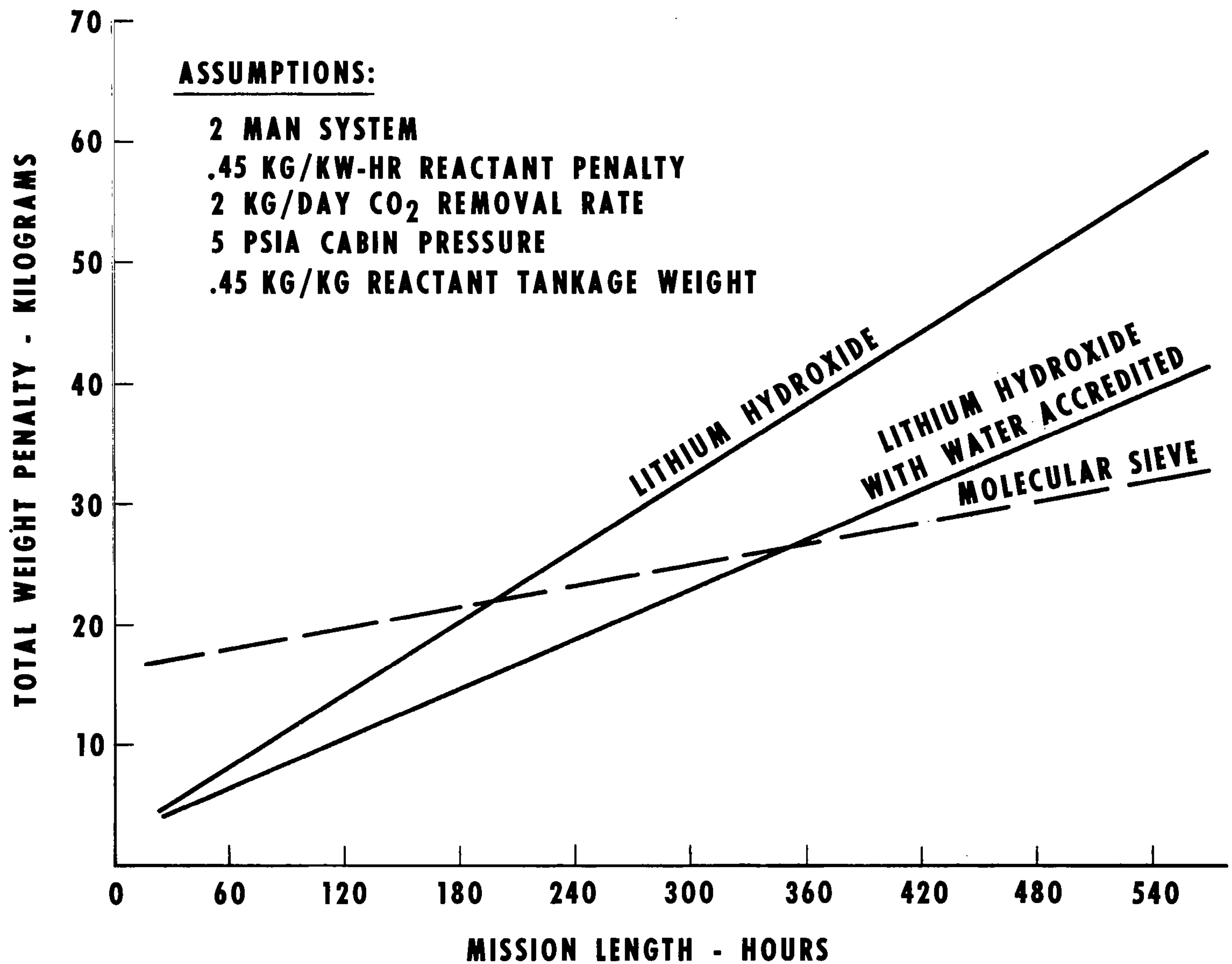

FIGURE 7. CARBON DIOXIDE REMOVAL SYSTEMS WEIGHT COMPARISONS

First of all the question is asked: What does one include in the weight estimate? Since no single subsystem will be an entity in itself, what portion of an integrated system can be considered belonging to one subsystem and the remaining to another? As an example, the radiators for both the power and environmental control systems in all probability will be integral with the payload's outer skin. Therefore, depending upon actual construction, a certain percentage of the radiator's weight should be considered as belonging to the environmental control or power system and the remainder to the payload's structure. In a similiar manner various subsystems require power and therefore their total weight should include an apportionment of the power system's weight. The power system weight penalty is highly dependent upon the total size of the system. If the environmental control system requires 500 watts, the fixed weight penalty associated with this requirement would be greater if it had to be obtained from a 2 kw source than from a 8-10 kw source. This is to say that the environmental control system's fixed weight penalty of a lunar roving vehicle (8-10 kw) would be less than that for a lunar shelter (2-3 kw). Secondly, in estimating the environmental and thermal control system's weight it is a necessity to have a good idea of the payload concept. Such factors as total volume to be conditioned, heat leaks, thermal loads, mission parameters such as airlock openings and duration within the enclosure, atmospheric leakage rates, external environmental exposure, and redundancy requirements to maintain a desired overall system reliability will play an important part in establishing subsystem and system weights.

One can consider the weight of an environmental and thermal control system as being composed of essentially two groups of weights. One group is fixed in nature such as compressors, radiators, sensors, valves, etc., and the second group is dependent upon the mission and its duration. To sustain an astronaut, certain amounts of life-supporting consumables such as food, water and oxygen must be provided. The weight of these items will be a linear function of mission length. Certain other items such as oxygen tankage, lithium hydroxide, power system reactants, and atmospheric leakage represent other expendable rates. However, for estimating weight penalties both these mission-dependent weights are normally grouped under one heading and constitute an overall expendable rate that must be paid for each unit of mission time.

To provide the reader with an idea of the weight required to sustain the life of two astronauts while participating in a lunar exploration, Figure 8 has been prepared. This figure shows the required hardware and expendable weights as a function of mission duration. The fixed hardware weight includes all items shown in Figure 3, with the exception of the radiator. Additional weight is included to cover such items as controls, sensors, ducting, piping, glycol, etc. Added to the constant fixed amount is an expendable weight which is dependent

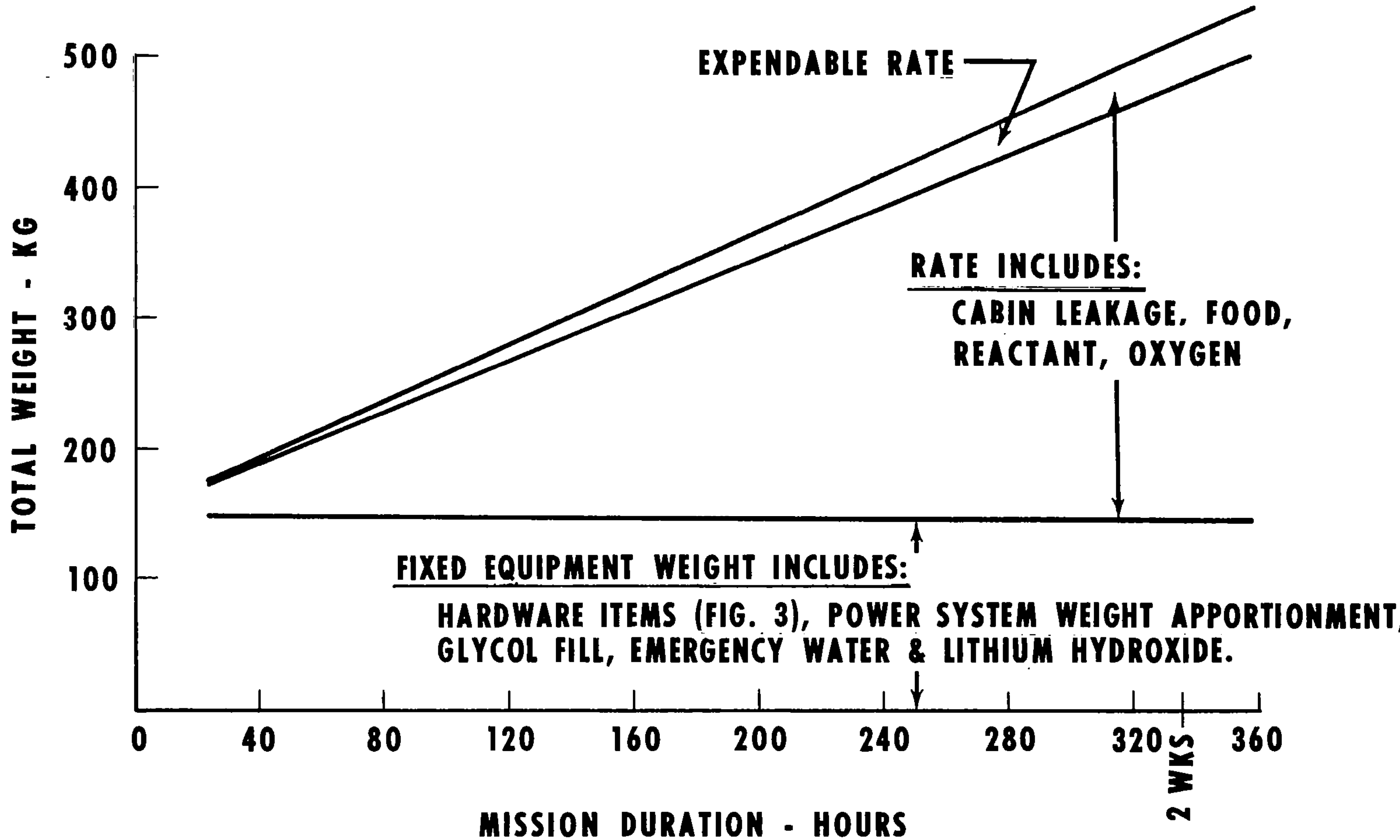

FIGURE 8. ENVIRONMENTAL AND THERMAL CONTROL SYSTEM'S WEIGHT ESTIMATE (2 MAN SYSTEM)

on mission duration. Since it is impossible to establish a precise expendable rate, both a minimum and maximum rate are indicated. This uncertainity is brought about largely by the fact that exacting thermal loads cannot be established. Consequently there exists some doubt as to the amount of power required to provide adequate thermal protection. In addition the trade-off of radiator size and power penalty had to be made in a rudimentary manner. The weight of such items as pressure suits, first aid kits, food preparation equipment and backpacks were not included. Selection of such items will be dependent largely upon the operational aspects of any given mission.

INTEGRATION OF ENVIRONMENTAL CONTROL SUBSYSTEMS

The environmental control subsystem shown in Figure 3 contains all the basic subsystems to perform the necessary functions required to sustain human life while on the lunar surface. It cannot be stressed too strongly that an optimum environmental control system for any given mission cannot be evolved without considering the many interrelationships involved with the other vehicle subsystems. The system shown is not meant to be the ultimate, but rather it shows one specific approach which could be utilized on a lunar mission. Although a quantitative performance analysis has been made on the system, the resultant information is of value only to the extent that it establishes that realistic flows, power, etc., are required for the desired performance. To establish precise and accurate performance and power penalties for a given system, one must analyze both the system and its many alliances with other subsystems. The term "integration" of subsystems implies more than just matching items such that the output from one causes the second to function properly. One must try to profitably employ the waste of one system by another system. In this regard, the conservation of water during a lunar mission will greatly reduce the logistics support. Man will require approximately 5 kg of water for each mission day and therefore without water reclamation the weight penalty associated with a two-man, two-week mission would approach 140 kg. Such an extreme penalty could not be supported by some of the early lunar mission payload capabilities. However, salvation lies in the fact that the waste product of the hydrogen-oxygen fuel cell is water. Hopefully, by proper integration of the power and life support subsystems, this water weight penalty can be reduced or completely eliminated on some lunar missions. Although integration obtains a savings in weight, there are precautions which should be observed when attempting to combine subsystems. As subsystems are integrated, one must rely upon or place more confidence in a particular component or subsystem. This unit must now function during operation of all integrated systems and therefore its failure rate must be lower. In addition, combining of subsystem functions may inherently lead to greater complexities, mainly in regard to repair and maintenance. Therefore, savings of weight and reactant consumption are not the only criteria upon which to judge the merits of an integrated system design.

Since there exist numerous integration possibilities a brief treatment of some potentialities might be interesting. Most planned lunar logistic missions anticipate some period of equipment storage prior to manned usage. Therefore to provide sufficient storage time with minimum weight and volume restraints, the reactants for the power subsystem and the atmospheric constituents will probably be stored in a subcritical cryogenic state. In this state these cryogenics will be at pressures higher than required for some operations. Here then exists a source of stored mechanical energy which could be released upon expansion. Rather than just throttling these gases, the gases might be expanded in a device such as a turbine which could possibly be used to drive a centrifugal water separator or cabin air blower. In such applications the savings in equipment weight would not play a big factor. However, any reduced power requirement with a subsequent reduction in reactant consumption might merit such an integration.

Since the oxygen and hydrogen reactants are stored at an extremely low temperature, they may be integrated with a thermal control system to provide a substantial heat sink. Besides being employed to supplement cabin or compartment cooling, the fluid could be used as a refrigerant for humidity control, to freeze out CO_2 or to reduce air temperatures in the regenerative molecular sieve system. In the environmental and thermal control system indicated in Figure 3, various items are shown which are correlated with others for weight, volume, or performance considerations. A regenerative heat exchanger is used by the catalytic burner to utilize the high temperature exhaust gases; an air glycol heat exchanger is included in the electrical coolant loop to supply heat when needed to the cabin or suit atmosphere; the radiator uses portions of the enclosure structure to mount the condensing coils; the atmospheric airstream velocity drives the centrifugal water separator; and the inherent pressure drop across the blower system provides the impetus to induce flow through the catalytic burner. In general one could say that systems integration can be accomplished by utilizing common fluids, structures, ducting and power shafts as well as putting to use the waste products of one component by another.

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Chapter 4
ADVANCED LIFE SUPPORT TECHNIQUES

By

Jerry L. Johnson*

INTRODUCTION

The problem of providing for man's vital requirements in an intolerable environment is as old as man's earliest efforts to extend his knowledge of the physical world. These requirements most probably have not changed significantly even unto this day. Whether man is exploring the poles, the ocean depths, steaming jungles, arid deserts, or space and the planets, the basic life support objectives do not change, only the techniques of implementation. Man's earth-based expeditions are satisfactorily supported by logistic and stockpiling measures; but technical difficulties, vehicle cost and weight limitations make this type of support for deep space missions beyond the initial lunar landings highly impractical if not entirely unfeasible.

The most effective manner of sustaining man for long periods of time with or without a minimum of logistic support, is to increase the efficiency of the supporting techniques. This requires the development of closed or recycling systems which can provide for man's requirements over long periods, independent of outside support. In such systems we are primarily concerned with those material necessities which are consumable and hence would normally require stockpiling or resupplementation by logistic support. However, one must not neglect to recognize, study, and resolve other important problems, such as those in the psychological, shielding, thermal control, and humidity control areas.

So let us now consider some of the various approaches, principles, and techniques which seem to offer the most potential for contributing to the development of such life support systems as would find application to the deep space or lunar base mission.

THE "IDEAL" LIFE SUPPORT SYSTEM

Ideally, the most efficient and desirable life support arrangement conceivable would be that of a completely closed or perfectly balanced ecological

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system. From a purely physical viewpoint, such an ideal system could be defined as one in which matter as such is not allowed to enter or escape the system. Obviously such a system must have zero material leakage, or waste, and must utilize energy as a means of effecting all internal ecological housekeeping chores. To be truly capable of indefinite operation all waste products in this system must be treated or reacted in such a manner as to effect a total reclamation in the form of psychologically and physiologically acceptable materials. These materials must be made available in balanced proportions, adequate quantities, and at times consistent with the basic life support requirements of the consumer organism.

Is it ever really possible, however, to achieve such an ideal life support system? Apparently so, at least in the case of the balanced aquarium (Fig. 1) wherein the waste products of the plant and fish mutually serve to fulfill each other's vital requirements. Only the plant, however, can directly manipulate, convert,and store ambient physical energy (light). This energy is stored by the plant as chemical energy in the form of mutually useful chemical compounds. In this closed system, it is primarily the plant therefore that provides this critical recycle mechanism necessary to maintain the ecology in a balanced state. But of course we must concern ourselves with man and his requirements. What constitutes such a system for man? Does not the total earth environment itself constitute man's closed system? (Fig. 2) Is it yet possible to define an even more habitable environment than that of earth, that to which we seldom give second thought? Is not what we are striving for in a life support system the same process which occurs on earth, except for differences in the relative quantity of masses involved, conversion rates, and manner of conversion? By virtue of the huge mass and volume of its biosphere, the earth has a large surplus of consumables and a large capacity for diluting or dispersing toxic concentrations to acceptable levels. These qualities afford us the luxury of lazy and complex recycle mechanisms in the life cycles of terrestrial organisms. Obviously the space life support system cannot afford these luxuries.

It seems that it would be very convenient indeed if we could compress or scale down our natural environment and package it for use as our extraterrestrial life support system. But first, perhaps we should have some idea as to what some of the more obvious constituents of our terrestrial environments are. (Fig. 3) These relationships of life and its environment make up the earth's ecology. These factors of our environment all influence and interact with man continuously. The resultant effects may be subtle and harmless, or even beneficial. On the other hand, grave and violent interactions having fatal consequences do occur quite frequently.

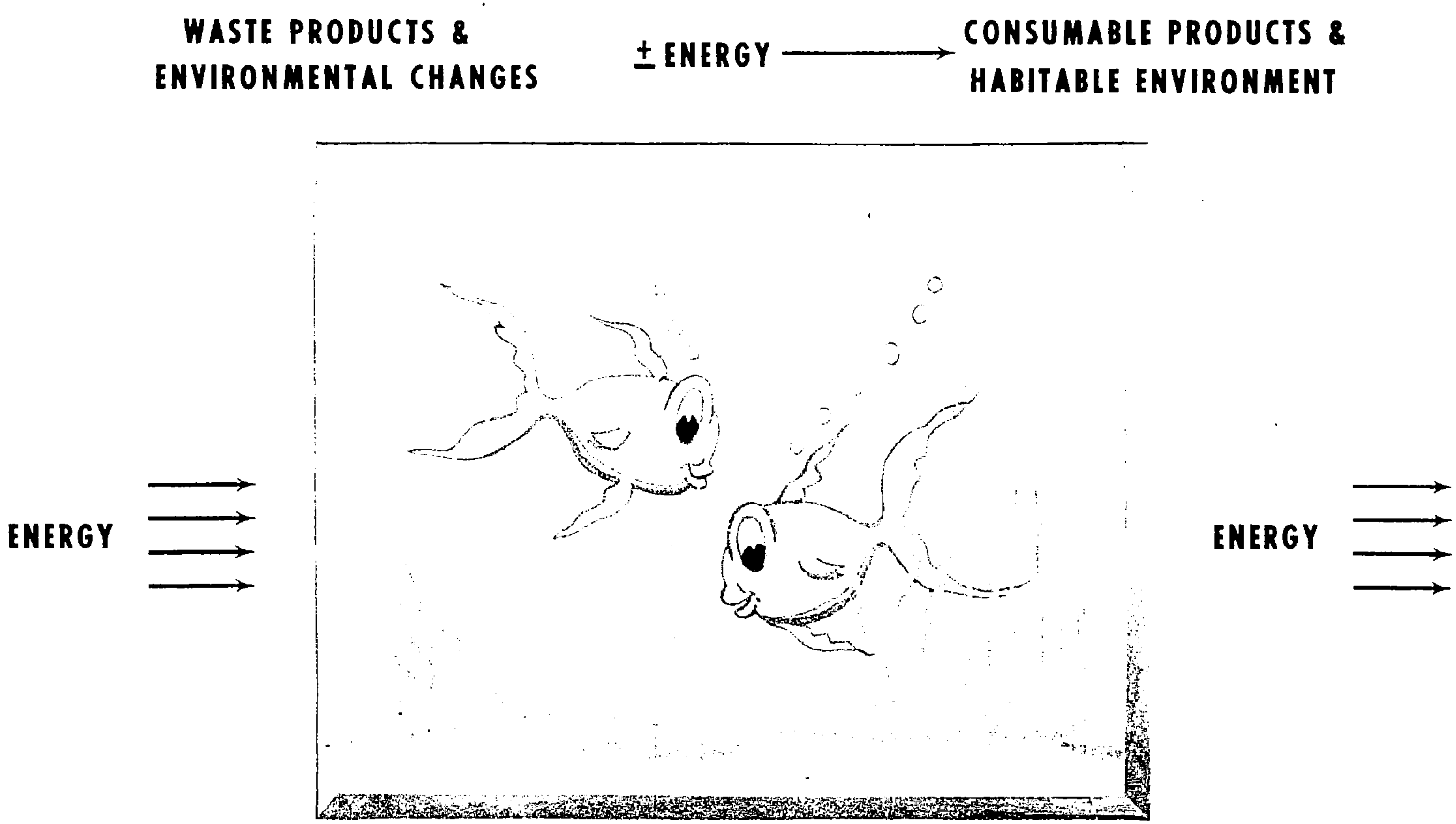

FIGURE 1. THE BALANCED AQUARIUM-A CLOSED ECOLOGICAL SYSTEM

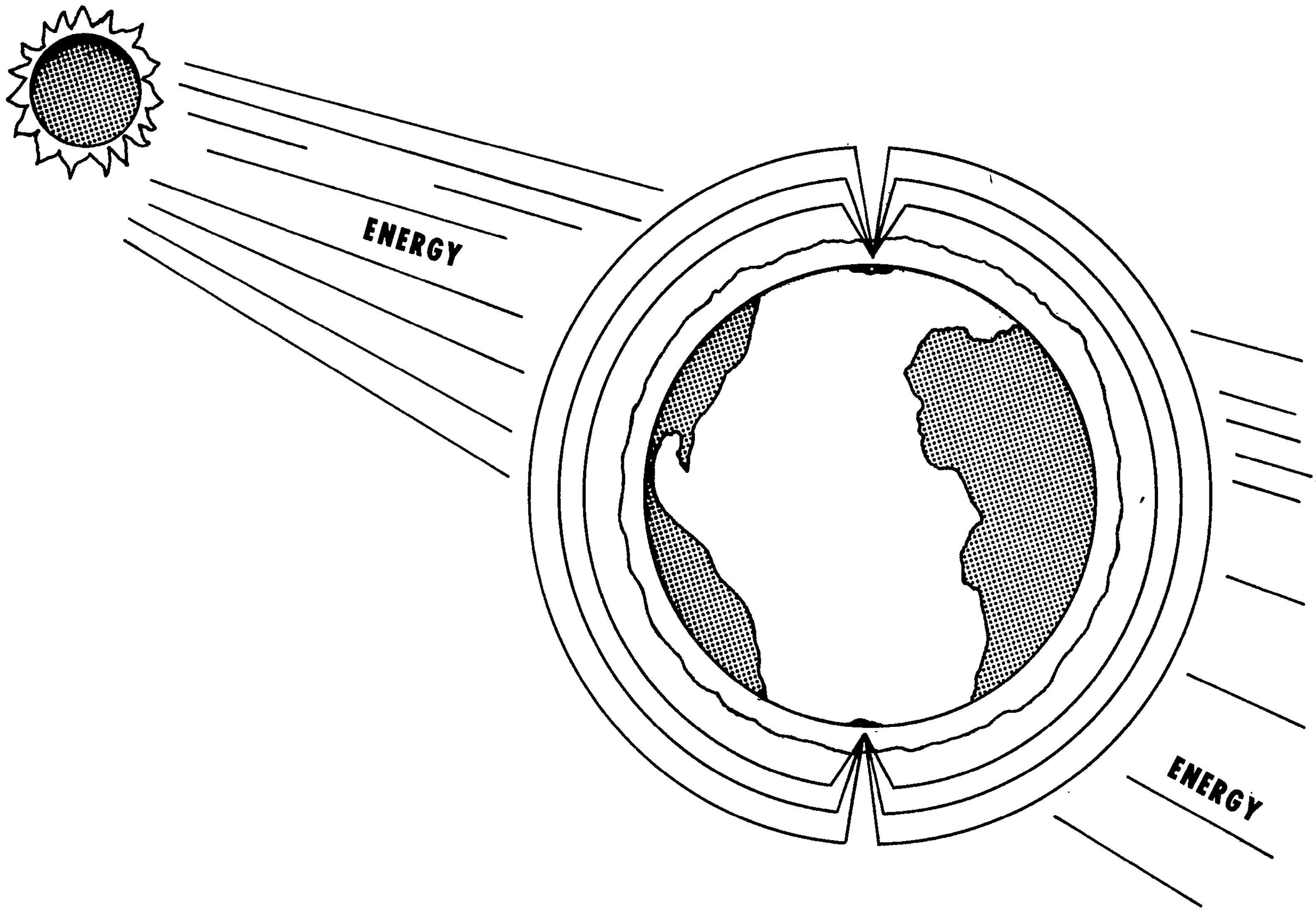

FIGURE 2. MAXIMUM HABITABLE ENVIRONMENT

I LIVING ORGANISMS

II PHYSICAL ENVIRONMENT

MATTER

GASES

ATMOSPHERE
TOTAL

1. PRESSURE (14.7 PSI)
2. PARTICULATE MATTER
3. WATER VAPOR
4. CHEMICAL COMPOSITION

GAS	% BY VOL
A. N_2	78.09
B. O_2	20.95
C. A	0.93
D. CO_2	0.03
E. Ne	0.0018
F. He	0.00052
G. CH_4	0.00015
H. Kr	0.0001
I. N_2O	0.00005
J. H_2	0.00005
K. O_3	0.00004
L. Xe	0.000008
M. NO_2	0.0000001
N. I_2	$2X10^{-11}$
O. Rn	$6X10^{-18}$

LIQUIDS

1. WATER
2. DISSOLVED & IONIZED CHEMICAL COMPOUNDS
3. PARTICULATE MATTER

SOLIDS

1. NATURALLY OCCURRING ELEMENTS
2. ORGANIC & INORGANIC CHEMICAL COMPOUNDS

ENERGY

1. SOLAR ENERGY
   A. PARTICLE RADIATION
   B. ELECTROMAGNETIC RADIATION
2. TERRESTRIAL ENERGY
   A. NATURAL RADIOACTIVE DECAY
   B. ELECTROMAGNETIC RADIATION
   C. ACOUSTICAL ENERGY
   D. GRAVITY FIELD
   E. MAGNETIC FIELD
   F. ELECTRICAL FIELDS
   G. OTHER SOURCES, I.E., EFFECTS OF THE KINETIC ENERGY OF THE MOTIONS OF THE EARTH AND ATMOS.

FIGURE 3. TERRESTRIAL ENVIRONMENT

Some of these relationships are very poorly understood or as yet even undetected; for example, how and to what extent does the earth's magnetic field benefit or harm us? What is the precise metabolic role of nitrogen and argon, two of the major constituents of our atmosphere? What happens to man when any one or all of these terrestrial factors deviate for unusually long periods from their normal conditions or vary beyond the limits of normal deviation? Of this total environment what then are man's absolute or minimum requirements? Figure 4 depicts in rough time units man's survival times versus his requirements for specific vital environmental factors. When one contemplates removing man from his total natural environment it becomes more obvious that not quite as much is really known about his minimum requirements as may once have been thought. In addition to life support criteria defined in terms of matter and energy, one other important quality must now be considered, that of time. We see that man's requirements can only be defined with respect to time, and that current knowledge can accurately define those requirements for only relatively short periods of time. Information relating to long term effects of even subtle changes in man's natural ecology is sadly lacking. However, we do know that the earth's total environment is acceptable to man for an indefinite period of time, or for his natural lifetime.

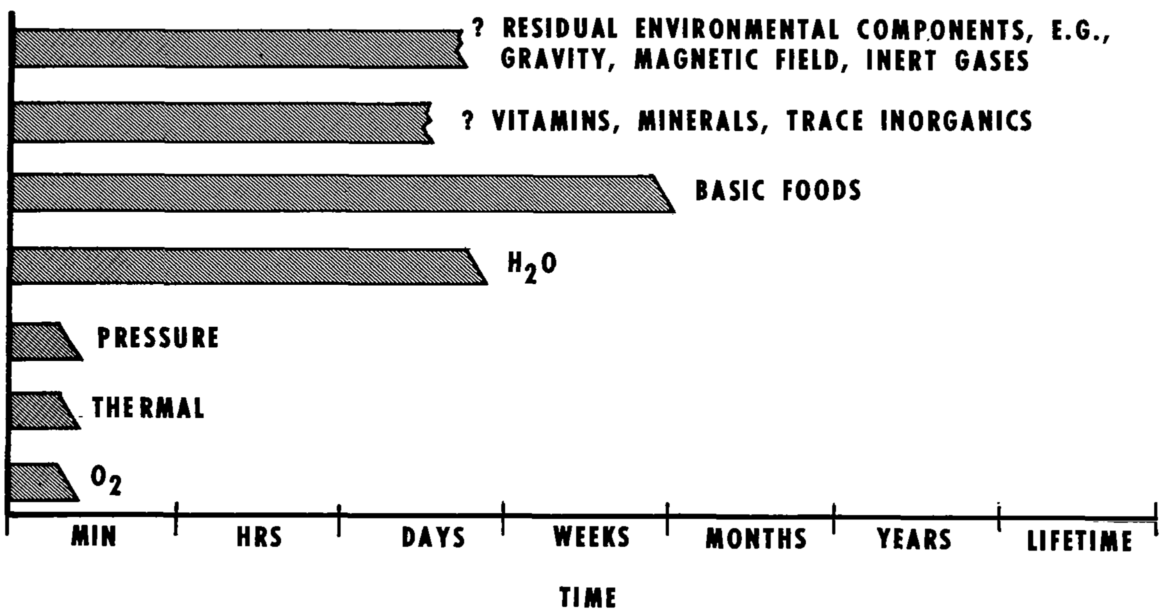

FIGURE 4. MAN'S REQUIREMENTS VERSUS TIME

One could now ask, then how is it that the earth's environment is produced or maintained? Is it fat with redundancies and non-necessities? What is man's minimum environment with respect to indefinite times? Is it feasible to scale down, or to apply natural mechanisms of ecology?

So let us examine those means by which our environment maintains itself by probing into the specific mechanisms of ecology. Hopefully, we might uncover how man's requirements are provided for by terrestrial processes and how we might possibly apply these mechanisms toward the development of advanced extra-terrestrial life support systems.

Let us start first with man's most immediate requirement, oxygen. Figure 5 lists some of those sources which have been suggested as significant contributors to the regeneration of oxygen. Photosynthesis is the major natural contributor, and in view of our current knowledge of the three sources, appears to offer the most potential for a life support system. However, the aerobic and anaerobic bacterial nitrogen fixation mechanisms are not as fully understood as yet and certainly the more direct formation of vital amines (Fig. 5, item 3) with oxygen as a byproduct does point up some highly interesting possibilities for an integrated bacterial system.

The earth's mechanisms for maintaining the carbon dioxide and nitrogen equilibrium are shown in Figure 6 along with the natural processes for water purification and particulate matter removal. Of these, the mechanisms of water purification appear most promising for adaptation to space missions. There is one other natural method by which the earth maintains its nitrogen equilibrium in addition to those mentioned in Figure 6. This is the purely physical phenomenon of nitrogen fixation by lightning discharge and a corresponding decomposition by photochemical reactions in the atmosphere. These types of physical reactions offer a potential direct and brute-force method of manipulating chemical energies at the expense of externally derived energies and will be given more thorough treatment as this discussion develops.

The natural means of contamination control of toxins (Fig. 7) is by dilution to harmless concentration levels and by oxidation to non-toxic compounds. This oxidation may be either a physical process or a biological one.

In addition, our environment also contains a whole array of organisms, some of which live internal to man. These parasites may range anywhere in size from viruses (submicroscopic) to tapeworms reaching many feet in length. As many as forty different types of micro-organisms and nine fungi have been identified as being native to the alimentary tract of a normal healthy man. In general, these micro-organisms are nonpathogenic in nature. However, like all organisms

MECHANISM	POTENTIAL APPLICATION
(1) PHOTOLYSIS-DISSOCIATION OF H_2O AT HIGH ALTITUDES $2H_2O \xrightarrow[\Delta\ 1000°C]{} 2H_2 + O_2$ (H_2 LOST TO SPACE)	(1) REQUIRES MORE POWER & IS TECHNICALLY MORE DIFFICULT THAN ELECTROLYTIC DISSOCIATION. $2H_2O \xrightarrow[e]{} 2H_2 + O_2$
(2) PHOTOSYNTHESIS-BY CHLOROPHYLL CONTAINING PLANT LIFE $CO_2 + 2H_2O \xrightarrow[\text{ELECTROMAGNETIC ENERGY}]{\text{CHLOROPHYLL CATALYST}} CH_2O + H_2O + O_2$ FORMALDEHYDE (CH_2O) POLYMERIZES TO CONVENIENT CARBOHYDRATES $C_6H_{12}O_6$	(2) DEFINITE APPLICATION (A) O_2 RECLAMATION (B) CO_2 LEVEL CONTROL (C) FOOD SUPPLEMENT (D) H_2O PURIFICATION
(3) BACTERIAL NITROGEN FIXATION- NET REACTION: $2N_2 + 2H_2O + 4H^- \longrightarrow 4NH^- + O_2$ POTENTIAL AMINE → N(H)(H)(CH_3)	(3) POSSIBLE LUNAR BASE APPLICATION PENDING FURTHER RESEARCH.

FIGURE 5. MAJOR SOURCES OF TERRESTRIAL OXYGEN

MECHANISM	POTENTIAL APPLICATION
CARBON DIOXIDE EQUILIBRIUM ATMOSPHERIC CO_2 BALANCE IS MAINTAINED BY EQUILIBRIUM OF DISSOLVED CO_2 IN OCEANS & PHOTOSYNTHETIC ORGANISM DEMANDS.	PHOTOSYNTHETIC GAS EXCHANGE SYSTEM FOR LUNAR BASE. POSSIBLE DEVELOPMENT OF A LIQUID MEDIUM CO_2 COLLECTOR.
NITROGEN EQUILIBRIUM ATMOSPHERIC N_2 BALANCE IS MAINTAINED PRIMARILY BY DENITRIFYING ANAEROBIC BACTERIA CAPABLE OF UTILIZING NITRATES & NITRITES AS OXIDIZERS FOR ORGANIC MATTER.	MAN'S REQUIREMENTS NOT YET ESTABLISHED.
WATER PURIFICATION MECHANISMS (1) SOLAR DISTILLATION (2) AERATION (3) ADSORPTION (4) ABSORPTION (5) RESPIRATION (6) FILTRATION	CONDENSATE FROM RESPIRATION IS MOST READILY PROCESSED TO POTABLE WATER. FOR LUNAR BASE, POSSIBLY RECOVERY OF PLANT RESPIRATORY WATER.
PARTICULATE MATTER REMOVAL (1) GRAVITY (2) SURFACE TENSION (3) ATMOSPHERIC CONDENSATION (4) ELECTROSTATIC AGGREGATION	POSSIBLE DEVELOPMENT OF AN ACCUMULATOR UTILIZING SURFACE TENSION OR ELECTROSTATIC PRINCIPLES.

FIGURE 6. TERRESTRIAL MECHANISMS

CONTAMINANT	CONTROL MECHANISM	POTENTIAL APPLICATION
CHEMICAL TOXINS	DILUTION, CONVERSION BY NATURAL OXIDATION	CATALYTIC OXIDATION, ACTIVATED CARBON
MICROORGANISM INTERNAL TO MAN	ANTIBIOSIS & ANTIBODY FORMATION	VERY IMPORTANT PROCESSES WHICH REQUIRE FURTHER INVESTIGATION IN A SPACE ENVIRONMENT SITUATION
MICROORGANISM EXTERNAL TO MAN	ANTIBIOSIS, ULTRAVIOLET RADIATION, AVAILABLE NUTRIENTS OXIDIZED AS FOOD BY HIGHER LIFE FORMS	ULTRAVIOLET RADIATION, CATALYTIC OXIDATION

FIGURE 7. CONTAMINATION CONTROL REQUIREMENTS

they are continuously mutating and under certain conditions, (e.g., space environment) there is some concern as to whether any of these could perhaps evolve into pathogens or toxin producing organisms. The prime question is: Will the space environment affect the natural processes which control bacterial populations internal to man?

Those micro-organisms which are external to man are of truly astounding variety and number. They are the most widespread form of life and for this reason have been selected as targets for extraterrestrial life detectors. Their mechanisms of metabolism are phenomenal and of utmost interest. Some micro-organisms can effect reduction of sulfates, selenates, phosphates, and CO_2. Others can rupture the extremely stable bond of the nitrogen molecule; some even are capable of oxidizing methane. It is also thought that certain photosynthetic bacteria essentially expire hydrogen rather than oxygen. These are the types of micro-organisms which have the potential of contributing to new life support system concepts.

Similarly impressive and somewhat inconceivable are the extreme environments in which some micro-organisms are found to survive, adapt, and proliferate. (See Fig. 8)

(1) H_2SO_4 (CONCENTRATED)

(2) SURFACE FILMS ON SALT CRYSTALS

(3) MINUS 20°C IN ANTARCTIC SALT PONDS

(4) 95°C WATER-NATURAL SPRINGS

(5) ATOMIC PILE CORES

(6) EXPLOSIONS

(7) HI-VACUUMS

(8) LIQUID HELIUM TEMPERATURE SEEMS TO OFFER EXCELLENT PRESERVATION

FIGURE 8. EXTREME MICRO-ORGANISM ENVIRONMENTS

It has not yet been demonstrated that micro-organisms cannot survive certain local environments of the moon, and until such time that it is so demonstrated, there always remains the possibility of contamination should a preserved organism be introduced into a favorable environment such as a lunar shelter or space cabin containing those ingredients conducive to its growth. So perhaps the astronaut should always remember to wipe his feet well prior to reentering his spacecraft abode.

Micro-organisms need not be thought of as exclusively harmful, for some types are certainly beneficial and necessary in controlling the waste of higher organisms. Here, the word "waste" is a relative term which requires identification with a given process. In nature there exists very little, if any, waste, for what is waste to some is food for others no matter how distasteful it may seem to human aesthetics. From Figure 9 one can see how utterly dependent all animals are on plants and micro-organisms for both food sources and contamination control or waste processing and reclamation. This relationship will be developed in greater depth and from other perspective views as we progress.

PHYSICAL PARAMETERS

Accurate descriptions of the mechanisms of biological effects of the gravity field have long been sought after (Fig. 10). The most meaningful direct approach toward determining these effects is to remove or null the factor in question (e.g., gravity). This is exactly the experimental procedure (the production of a null gravity or weightless condition) which has finally become technically feasible to realize via earth orbital satellites.

NASA's current biosatellite program heavily supports cellular and subcellular level experiments which hopefully will contribute substantially toward the definition of long term biological effects of acceleration and/or lack of acceleration. The results of this program should serve to establish proper orientation for our manned orbiting laboratory experimental programs and even possibly yield new information directly applicable to all manned space missions of the advanced or long duration types.

The frog egg is known to require gravity orientation; it proceeds to develop abnormally when reoriented once development has begun. Rodents, when given an opportunity by centrifugation techniques to indicate a preference of acceleration level, reportedly have chosen a value somewhat greater than 1G. However, all factors are not known in these experiments and it may well be that they are merely exhibiting a preference for the lower angular displacement rate rather than for greater acceleration per se. It has been demonstrated on the common chicken that morphological changes in succeeding generations result

WASTE MANAGEMENT	POTENTIAL APPLICATION
STEPPED DECOMPOSITION PROCESS PERPETUATED BY SPECIFIC TYPES OF MICROORGANISMS.	BACTERIAL WASTE PROCESSING SYSTEMS
NORMAL END PRODUCTS OF MICROORGANISM METABOLISM OF PROTEIN ARE; H_2O, CO_2, & NH_3	

FOOD SOURCE	POTENTIAL APPLICATION
I. DIRECT SYNTHESIS BY PHOTOSYNTHETIC ORGANISMS*	PHOTOSYNTHETIC SYSTEM
II. INDIRECT SYNTHESIS BY ANIMAL ORGANISMS	PHOTOSYNTHETIC FOOD SUPPORT FOR LUNAR ANIMAL COLONIES

*WITH THE AID OF VARIOUS N_2 FIXING SOIL MICROORGANISMS

FIGURE 9. TERRESTRIAL MECHANISMS

	POTENTIAL APPLICATION
GRAVITY FIELD THE MECHANISM BY WHICH THE EARTH EXHIBITS THE CHARACTERISTIC OF GRAVITY IS UNKNOWN. CENTRIFUGATION PRODUCES THE SAME END PHYSICAL RESULT, BUT ITS BIOLOGIAL ADEQUACY AS A SUBSTITUTE FOR GRAVITY REMAINS TO BE PROVEN.	MINIMUM REQUIREMENT UNDEFINED
MAGNETIC FIELD THE EARTH HAS A FIELD INTENSITY OF APPROX. .5 GAUSS. BY COMPARISON THE MOON'S MAGNETIC FIELD IS THOUGHT TO BE APPROXIMATELY 10^{-5} GAUSS.	MINIMUM REQUIREMENT UNDEFINED
ELECTRIC FIELD (1) VERTICAL FIELD GRADIENT OF EARTH-APPROX. 130 V/M (2) LOCALIZED AREAS OF IONIZATION-E.G., ELECTRONIC EQUIPMENT, FIRES. (3) STATIC CHARGE & DISCHARGE-E.G., ATMOSPHERIC CHARGE & LIGHTNING.	MINIMUM REQUIREMENT UNDEFINED

FIGURE 10. PHYSICAL PARAMETERS

from prolonged centrifugation greater than 1G. The nature of this change is an increase in the size of the bone mass in the chickens' drumsticks.

Prolonged centrifugation studies are currently being conducted by Dr. Jiro Oyama at Ames Research Center. They indicate inhibited growth rates in young mice accompanied by loss of body weight during the first 10 days, after which the growth rate parallels that of the control mice. When these adolescent mice have been subjected to some 80 days of continuous centrifugation, an apparent equilibrium in body weight is achieved which is inversely proportional to the G-loading. This seems to indicate that the body requires a certain amount of energy merely to maintain itself. Any imposition of added stress must be countered by the expenditure of more energy, thereby causing a decrease of the total available metabolic energy. Metabolic balance could then be explained to compensate by shifting in favor of a decrease in the amount of body tissue. This would infer, of course, if we dare extrapolate in the opposite direction, that weightlessness, all other factors remaining the same, could conceivably favor increases in body weight.

Although studies of both high and low magnetic field effects on biological subjects have increased severalfold of late, there is still no conclusive evidence defining the biological significance of the earth's magnetic field. Despite this lack of evidence, observations of the apparent effect of magnetic storms* on patients suffering from tuberculosis, cardio-vascular ailments, and leukemia continue to be witnessed in our medical centers. During such storms, the condition of patients with high blood pressure and heart trouble worsens, myocardiac infarction deaths increase, as do hemorrhages from tuberculosis. While such a correlation is most probably not generally accepted, a more suitable or credible explanation of some other affecting mechanism coinciding with the storms and clinical records has not yet been advanced. Some low field preliminary studies at 10^{-3} gauss (10^{-7} tesla) seem to indicate a reduced activity in mice. High field experiments at levels of 40-100 kilogauss (4-10 tesla), with a field gradient slightly greater than 6 kilogauss/cm (0.6 tesla/cm), had lethal effects on Drosophila when exposed for one hour periods. (Dr. Dietrich Beischer - US NAVSCHAMED). Subsequent experiments at higher gradients and repeated shorter exposure times totaling one hour seemed to confirm that the effect was not cumulative. It, therefore, seems that it is the field gradient rather than the field intensity that accounts for the more dramatic magnetic field effects.

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* These storms are caused by bursts of charged particles, originating from increased solar activity, interacting with and producing disturbances in the earth's magnetic field.

Some verification of protective effects of magnetic fields against whole body radiation in mice has been established by Dr. Cornelius Tobias and N. M. Amer of Berkeley, California.

This appears to be a potentially rewarding avenue of research worthy of further investigation, as a magnetic field does seem to have some definite effect on blood producing organs. It has been demonstrated that the white blood cell count increased or decreased and the red blood cell count increased by magnetic fields (perhaps by varying the homogeneity of the field). Therefore, it is conceivable that these effects could be made which would directly oppose those effects produced by ionizing radiation.

As to whether plants are affected by magnetic fields, there is wide divergence of opinion and experimental results in the literature. However, at a basic level, increased photosynthetic activity in chlorophyll extractions at 28 kilogauss (2. 8 tesla) has been reported.

In addition to the magnetic field, the earth also possesses an electric field. It seems that the solid earth has an excess of negative charges, which causes a steady drift of positively charged ions from the atmosphere toward it. The specific mechanism which provides for electron exchange in the opposite direction is uncertain; however it is generally accounted for by a mean earth population of some 2, 200 thunderstorms. One of the most common effects of concentrated electric charges in the atmosphere is the production of ozone from oxygen. For this reason, it is difficult to separate the pure biological effects of ions from those of ozone. High concentrations of ozone are dangerous to life primarily due to its instability and high oxidizing potential. Quantities of ozone seem to be higher than normal in pine forests and during electrical storms, producing pungent odors. In general, ionized air seems to produce physiological effects on man. Both positive and negative ions have been claimed beneficial to health although generally it is felt that positive ions are depressive and negative ions are invigorating. Some of these claims include the relief of emotional tension, freeing of clogged breathing passages in asthmatic cases, or unexplained relief and energy for some people. It is interesting to note that some famous health resorts have been found to have higher ozone concentrations than normal. A simple device to produce ionization of air consists of an ultraviolet bulb and an electric fan to force a stream of air over the bulb. Space radiation can also cause atmospheric ionization.

ECOLOGICAL MECHANISMS

As we have observed, for the most part our environment is maintained in a state of dynamic equilibrium by the interrelationships of the respective requirements of the organisms living therein.

Reviewing the requirements of these organisms, we find that they must have an energy source and some mechanism which makes possible the storage and internal manipulation of energy. The primary source of the earth's energy is of course our local star, the sun; this energy is in the form of electromagnetic radiation.

It has been proposed and widely accepted that this stellar energy is derived from a series of nuclear level reactions in which the most probable elemental mechanisms are carbon, hydrogen, nitrogen, and oxygen. At what might be considered to be a secondary order of reaction, interactions of the compounds of these same four elements at the molecular level are the mechanisms which enable terrestrial organisms to carry out the many various types of energy and chemical manipulations so essential to their existence. This series of reactions constitutes what are commonly referred to as the carbon dioxide and nitrogen cycles which can be expressed in block diagram form (Figs. 11 and 12). This is a general description of the manner in which the four basic elements of life are shuffled about.

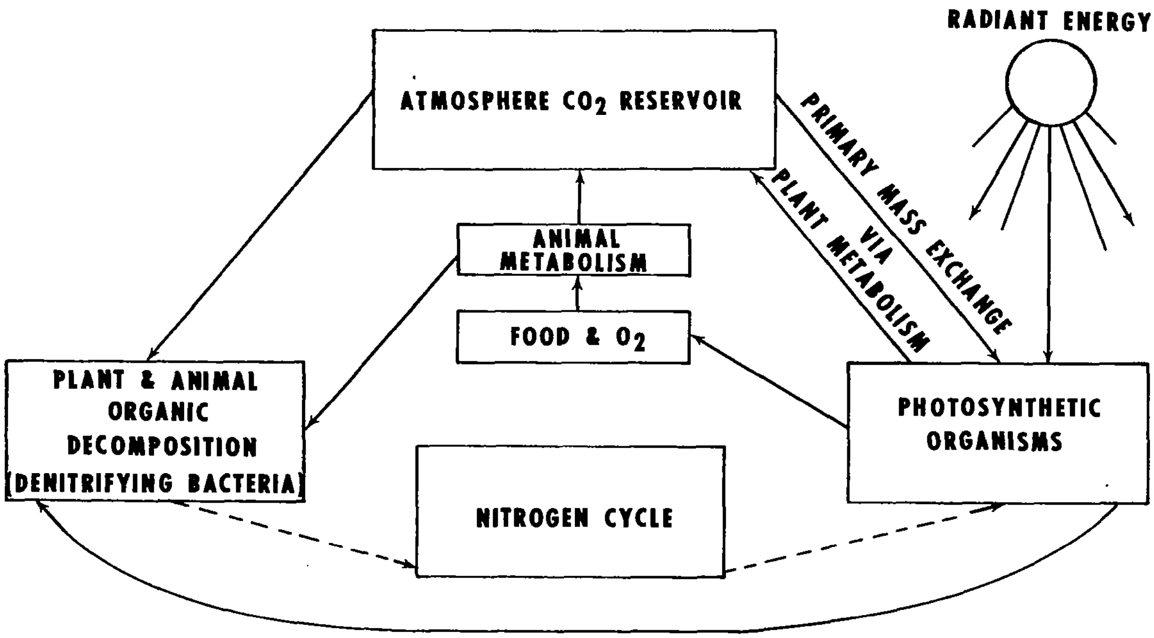

FIGURE 11. CARBON CYCLE

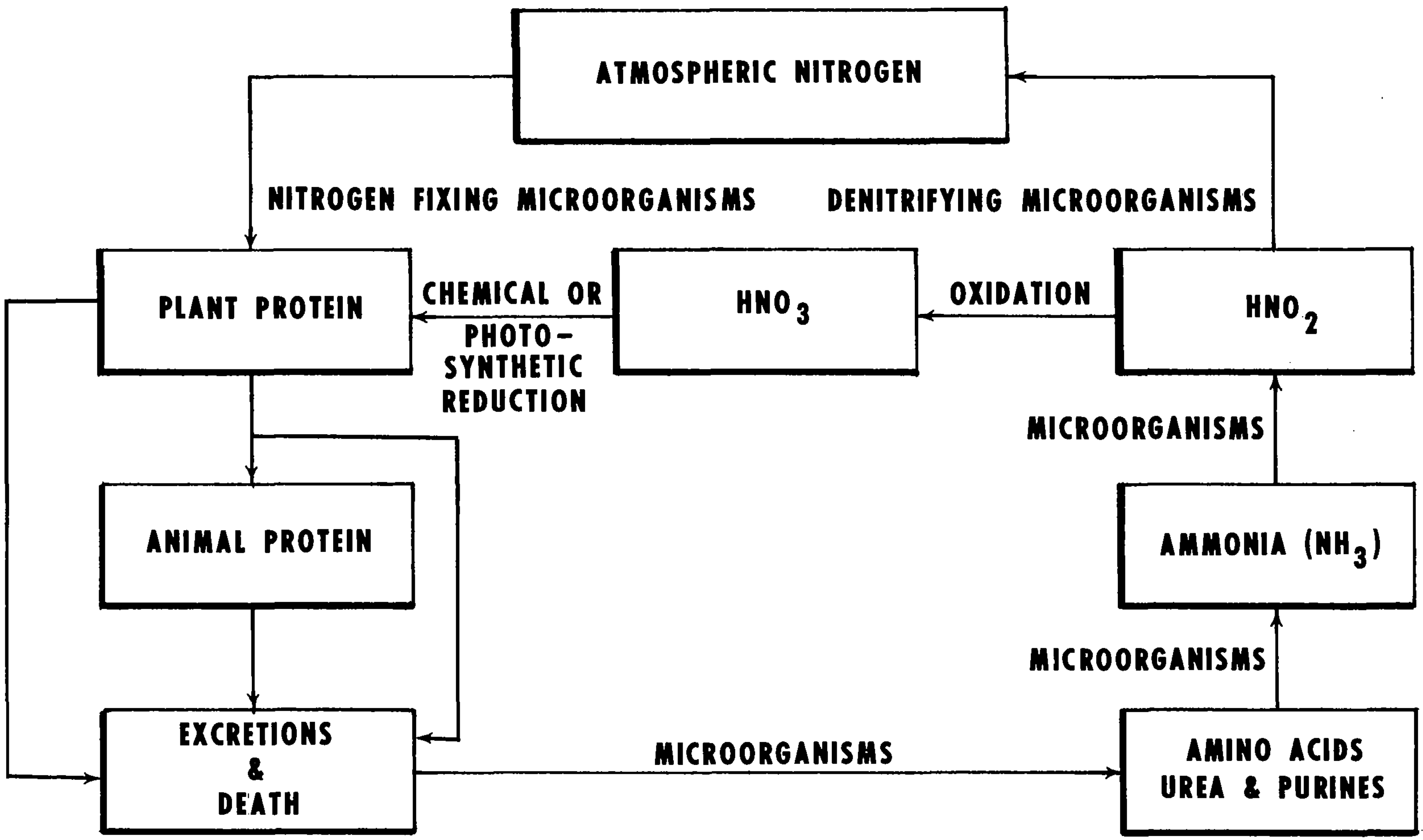

FIGURE 12. NITROGEN CYCLE

It should be noted that in both the carbon and nitrogen cycles, animal life is a more or less minor side loop which is not vital for the plant life to survive. It appears that it is the animals who are getting the free ride. However, if we take a closer look, we see that the plants would have a difficult time if it were not for the micro-organisms. And perhaps the micro-organisms are even dependent upon specific viruses ... et cetera ad infinitum.

For the most part, water may be considered to be a stream flowing through and purging these life cycles while simultaneously assuming the role of participating catalyst and transport medium. In addition it may also serve as an expendable coolant for regulating body temperature in some instances. The rejected water containing metabolic residues is purified, as previously pointed out, by physical and biological means.

In general, it can be stated that nature seems to take the path of least resistance energywise, with little regard to organism, catalyst, or reaction complexity. In contrast she seems also to be quite conservative of her four basic elements of life, first by directing her efforts toward reducing all organic materials to simple inorganic compounds, namely CO_2, NH_3, and H_2O, and then by proceeding to build them up to highly complex carbon compounds, thus recycling them over and over again. She has even succeeded in converting seemingly non-utilizable waste products (e.g., cellulose) of some organisms, into some form of nourishment for other life forms. This is done by means of incorporating almost inconceivable ecological chemistries into the life cycle of some types of organism, thus again closing the cycle where it may have first appeared to be gapping. For instance let us consider a process by which nature manufactures food from inorganic materials. (See Fig. 13.) Plants, with the exception of a few unicellular animals which contain chloroplasts, are uniquely capable of synthesizing food from totally inorganic compounds, provided that CO_2 is conceded to be inorganic. All other life forms, including man, must ultimately recognize their dependence upon the process of photosynthesis as a source of food.

MAN'S REQUIREMENTS OF FOOD

The body chemistry of man is highly complex and not really well understood (considering estimates of between 65,000 to 650,000 biochemical components still requiring isolation and identification). Nonetheless, that basic raw material input which is definitely necessary to sustain life seems to consist of relatively simple compounds -- these being O_2, H_2O, and food, in the order of their respective time dependency to man. These three materials are precisely those manufactured by our photosynthetic organisms. In addition, plants also manufacture and incorporate into their systems amines or carbon-nitrogen bonded compounds which they in turn polymerize or react with other carbon compounds

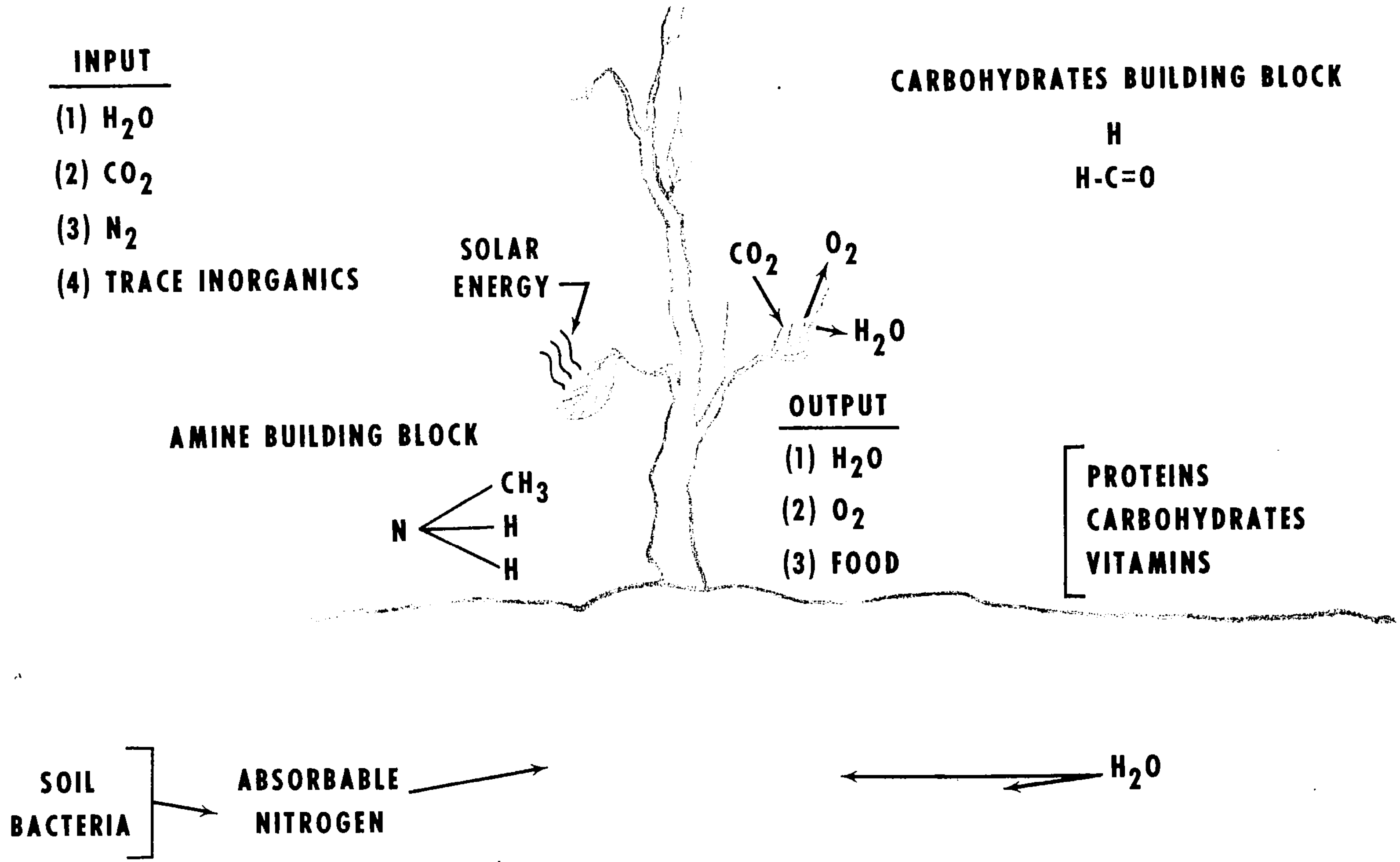

FIGURE 13. PLANT PHOTOSYNTHESIS

and minerals to give rise to a multitude of nutritionally essential and complex substances such as amino acids, proteins, vitamins, and enzymes. On the other hand, all that seems to be required by the plant is that which is produced or rejected by man, namely CO_2, H_2O, nitrogen (in usable form), and other mineral inorganics.

Why then is the plant life cycle not necessarily ideal for our space application? The reason is that while the cycle is indeed ideal, the rate at which the cycle proceeds, or time of product availability, certainly is not, particularly in the cases of the higher plants. Their photosynthetic efficiency is also very poor; however, photosynthesis of algae and bacteria, which have relatively shorter life cycles, has for some time been considered to be more applicable. The major disadvantage of any type of plant system serving as an exclusive food source is that of nutrition. Man apparently requires approximately 8 specific amino acids to promote the synthesis of all other amino acids from which the body proteins are in turn synthesized. Although all 8 of these are present in algae, the proportional distribution of those amino acids containing sulfur (cysteine and methionine) is such as to require the intake of about 6 times as much algae protein as meat protein in order to meet man's quantitative requirements for these specific types of amino acids. Since single plant proteins are deficient in some of these essential acids, it has been suggested that a variety of plant proteins be included in the diet. It has been estimated that a minimum of five specifically selected plants can fulfill man's nutritional requirements. Thus one of man's seemingly psychological biases, that of variety, is given some physiological support. However, none of the preceding discussion is meant to preclude that any one particular plant protein could not serve well as a food supplement.

REGENERATIVE SYSTEMS

What then is the current status of advanced life support systems; those which are capable of reclaiming at least some portion of human waste?

Some of the more advanced types of regenerative systems were proposed by Dr. Robert D. Gafford in a presentation at the American Astronautical Society's symposium on The Exploration of Mars, which was held June 1963 in Denver, Colorado.

One of the systems utilizes algae in a photosynthetic gas exchanger. As can be seen from the schematic drawing (Fig. 14), the basic materials (CO_2, H_2O, NH_3, and inorganic salts) for photosynthesis are fed into the exchanger from the electrochemical waste converter which will be discussed in detail later. Processed algae from the exchanger have been proven capable of providing at

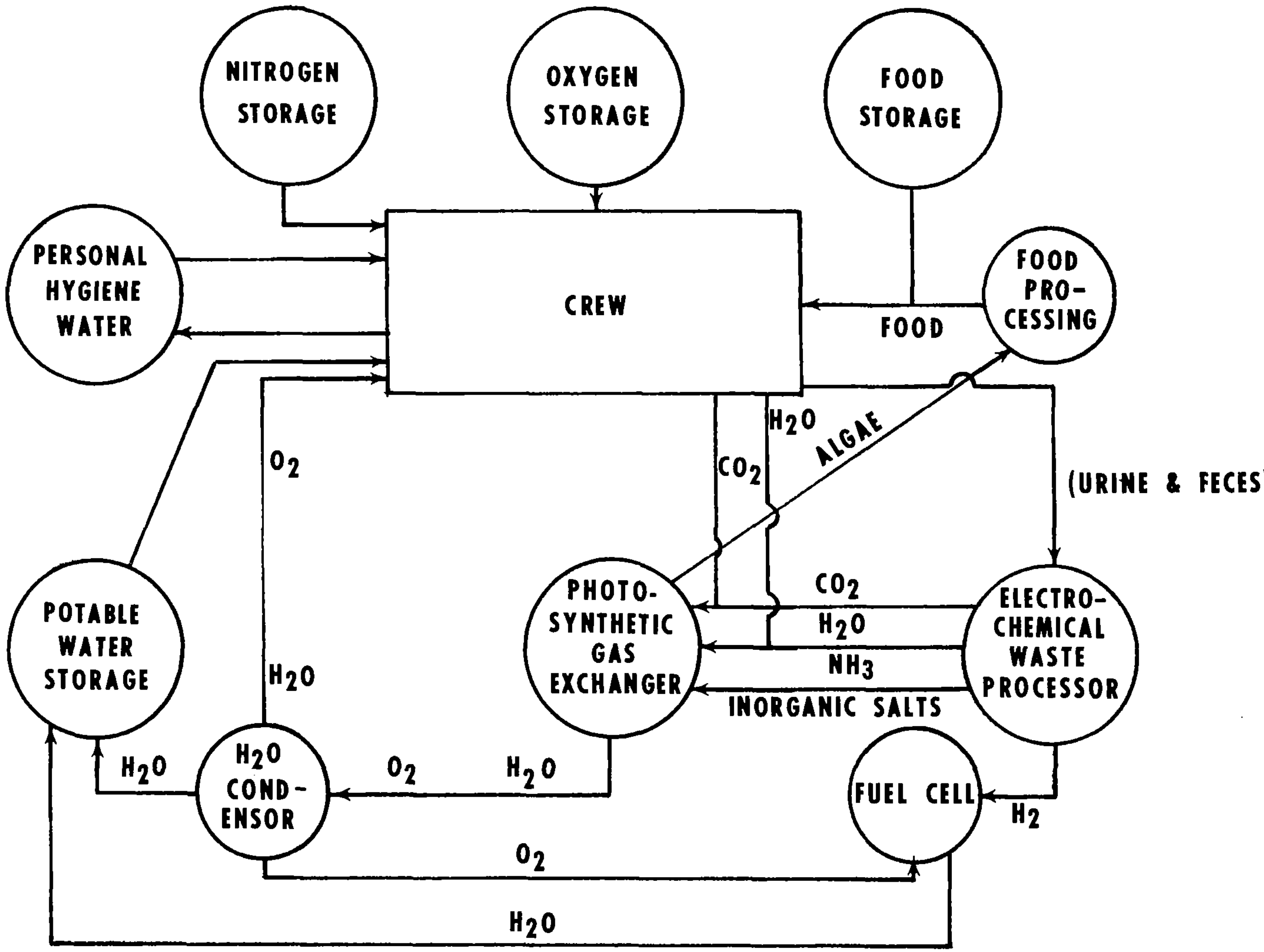

FIGURE 14. ALGAE SYSTEM

least one-third of the nutritional requirements of the crew; possibly as much as one-half will eventually be realized. Even then, there is an excess of algae available which very possibly could be converted to animal protein by feeding it to smaller edible animals. Water and oxygen leave the exchanger together and are separated in the water condenser, at which point the water may be treated for bacteria and stored. The oxygen is directed to a fuel cell which in turn reclaims in part some of the energy consumed by the electro-chemical waste processor, and the photosynthetic gas exchanger. In general the system concept of the photosynthetic process is believed to be somewhat parallel to and is considered to be as reliable as those biological systems utilized by our winery and brewery industries. The current problem areas of this system are those of nutrition, material balance, and system control.

Solar radiation is certainly an adequate and desirable primary energy source for this system, provided that a practical means can be devised to transmit this energy through the cabin's skin to the algae. The solar energy profile for a 420 day-Mars mission has been calculated and it appears quite favorable for such systems. Should this scheme prove to be impractical, then artificial illumination must be used at the expense of low energy conversion efficiencies of electric lamps (optimistically estimated to be around 20%). Due to this low conversion efficiency it is felt that nuclear, rather than solar cell, power will be needed for this type system.

The final key subsystem in this schematic is the electrochemical waste processor, described by Dr. R. G. Tischer at the 17th General Meeting, Society for Industrial Microbiology, August 1962. This processor essentially effects complete oxidation by electroytic technique. It is interesting to note that the effluent materials are precisely those produced by bacterial oxidation of protein. In this process the raw materials (urine and feces) are very finely homogenized in the approximate proportion in which they are excreted. The resulting organic slurry is transported to an electrolytic cell and a voltage of approximately 30 volts dc is applied. In addition to vigorous gaseous evolution there is produced an effluent liquid which is water clear and an optionally sterile solution of inorganic salts with a small amount of inorganic precipitate (carbonate and phosphate). Simple distillation should be adequate to make this water potable. Although the system has been modeled and demonstrated, it has not yet been optimized with respect to raw material concentrations, electrode spacing or voltage and current density. However, stirring is definitely known to be helpful. As for power requirements, preliminary indications are that they may be under 200 watts per man. The major problems of this technique are those of system control and electrode crusting. If the system is operated at too high a reaction rate, chlorine gas is liberated from the sodium chloride present in the raw materials.

The final system (Fig. 15) is one which utilizes a species of bacteria known as hydrogenomonas in the chemosynthetic gas exchanger. Essentially this bacteria reduces CO_2. The energy which it uses to accomplish this feat is derived from the oxidation of hydrogen. The energy conversion ratio is approximately 2 molecules of hydrogen oxidized per molecule of CO_2 reduced. Thus, oxygen and hydrogen must be supplied by means of electrolysis from the electrochemical waste processor. This of course requires more energy input into this processor than into the previous system. However, an advantage is realized in this system due to the increased energy conversion efficiency of electrolysis (approximately 80%) over artificial illumination techniques (20%). Only when more efficient conversion techniques are available to the photosynthetic systems, would they become competitive energywise with this method. Obviously this method does offer a decided saving in energy. The rest of the system is straightforward and is essentially the same as the previous one. The primary areas in question in the development of this type system are: 1) nutritional value of the bacteria to man, and 2) nutritional value of the waste processor effluent to the bacteria.

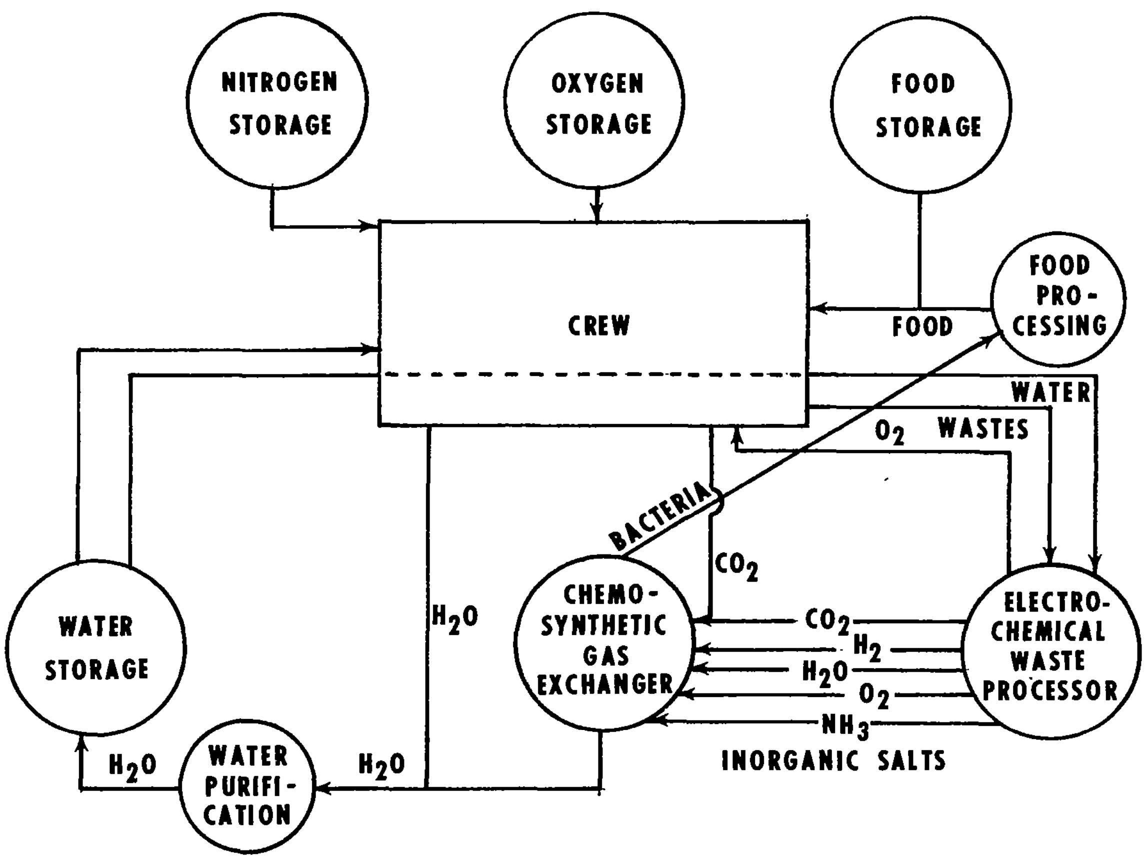

FIGURE 15. BACTERIAL SYSTEM

PHYSICOCHEMICAL SYNTHESIS OF FOOD

It has been suggested that perhaps it need not be necessary to reduce all waste organics to their simplest compounds (i.e., CO_2, NH_3, and H_2O), as nature tends to do; instead, it may be possible to break down incompletely oxidized waste organic fragments and then repolymerize the resulting fractions into various nutrients. In addition to excellent yields (near 100%), a minimum of energy should be required for molecular recombination. The opposition to this approach contends that human digestion is usually a very efficient process and expresses serious doubt that any significant quantity of substances of nutritional value would be available from fecal material. Even if feasible, this most direct technique of reconstitution of food would most certainly regenerate problems of psychological acceptance. However, natural ecological processes, as previously pointed out, eventually lead to the same end - that is, the reconstitution of food. But of course, we have no qualms about accepting food from these sources because nature is kind enough to provide our delicate sensibilities with a series of shields or buffers. These shields are in the form of the many-stepped, time-consuming biological reactions which (reassuringly to us) constitute purification processes of remote connection to human waste materials. Therefore, perhaps it would seem more palatable to man if his foods were synthesized in a similar manner.

So let us see whether it is possible for man to manufacture synthetic foods from the same inorganic compounds as plants do. Let us see how far we can go towards counterfeiting nature's vital products from scratch and for the time being without regard to power consumption or quantitative yields.

In Figure 16 it may be noted that methane and water are readily formed by reacting carbon dioxide with hydrogen. Adding ammonia to these products, then applying any one of the listed energies results in the production of building block type compounds vital to all life processes.

Although these are the classic Miller and Urey type experiments primarily seeking pre-biological chemical pathways for the origin of life, there is no reason why those who are currently more concerned with the maintenance of life rather than its origin should not take note of the status and of some of the interesting results of these works.

The amino acids produced in the manner indicated in Figure 16 include six of the eight necessary for protein synthesis which the body itself cannot synthesize. Two other amino acids (cysteine and methionine) were not expected to be present, as they contain sulfur and no sulfur was available in the system. It is strongly suspected that, were it to be made available (perhaps as H_2S) these critical amino acids would most probably be formed also.

NICKEL CATALYST

$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$ (SABATIER)

APPROX. 400 °F

$CH_4 + NH_3 + H_2O \longrightarrow$ 14 AMINO ACID, ADENINE, ATP

ENERGY
900°C,ELECTRIC ARC,UV,
ELECTRON, OR RF IRRIDIATION

POLYMERIZATION

AMINO ACIDS $\longrightarrow$ "PROTEINOID"

Δ

THERMAL SCHOCK

FIGURE 16. PHYSICOCHEMICAL SYNTHESIS

It has long been known that proteins can readily be hydrolyzed or broken down into their constituent amino acids. Chemical methods of simple protein synthesis have been possible for some time, but only recently has some demonstration been made that seems to indicate the feasibility of precipitating this synthesis by thermal techniques. Dr. Sidney Fox of Florida State University is credited with this accomplishment. This method for polymerization of amino acids can be accomplished in the following manner: amino acids in certain proportions (usually in a 4 to 1 ratio of aspartic acid, which is one of the amino acids, to each of the other seventeen or so amino acids) are thoroughly mixed and reacted at a specific temperature in a non-oxidizing atmosphere. The reacted material is then placed in a cellophane bag for dialysis. This straining or diffusion process is useful in separating the larger more completely reacted molecules from the smaller less completely reacted ones. In this manner a concentration of the fully reacted material is achieved.

Upon analysis, this material is found to contain long-chain carbon molecules in the same molecular weight ranges as simple proteins. In addition, the presence of fatty acids is suspected, though as yet unconfirmed.

This substance has been found nutritionally acceptable to rats and to micro-organisms which have nutritional requirements similar to those of man. This synthetic also gives the same standard color reaction and infrared absorption spectrum as natural proteins. Certainly there are some very important differences between the two; one is that of relative solubilities; another much more significant deviation is that both d and ℓ forms of amino acids are obtained upon breaking down the synthetic material whereas only ℓ forms are observed upon breaking down natural proteins.* Although some differences do exist, this material does certainly exhibit most of the nutritional qualities of natural proteins.** It is imperative that one does not over-call his hand in making this analogy. Hence, with due caution, the term "proteinoid" has been coined to more accurately define the true nature and origin of this substance.

One other interesting side property of this "proteinoid" is its ability to form small uniform spheres when placed in a small amount of water and thermally shocked (Fig. 17). These tiny regular spheres are known as "microspheres," and can be made to range in size from .5 to 50 microns or larger, by controlling various environmental factors (e.g., pH levels, cooling rates and concentrations). Some resemble living cells morphologically to an amazing degree, and are being considered as potentially useful in cell model synthesis.

These things man has done at the expense of power, time, and complex techniques. Our drug industries, however, have proven it economically and technically feasible to synthesize other complex organics, such as vitamins, antibiotics, and hormones. Nevertheless, in some instances the synthesis of certain substances (e.g., G-penicillin) still remains more efficiently or economically derivable from biological sources.

We can conclude that physicochemical synthetic recycling of foodstuffs is technically feasible, but the development of a practical system concept must await the results of more advanced and specifically applied research.

Also, it is yet to be determined whether such a system would be optimal when compared to a less radical interim system utilizing perhaps both biological and physicochemical techniques.

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* Optically active compounds which cause a plane of polarized light to rotate to the right are termed dextrorotatory (d) while those which cause the plane to rotate to the left are called levorotatory (ℓ).

** The natural or "ℓ" forms of the amino acids are much more readily assimilated than are the "d" forms.

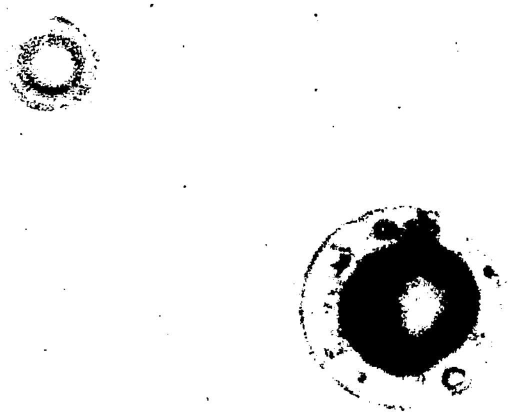

FIGURE 17. "PROTEINOID" SPHERES

CONCLUSION

In summary, one should re-emphasize those points which will be helpful in optimizing our advanced life support systems:

(1) It is necessary to define man's minimum environment with respect to time.

(2) It is necessary to define, as nearly as possible, man's total extraterrestrial environments.

(3) It is desirable to conduct a more thorough study of the earth's ecological mechanisms (in particular micro-organism metabolisms) while bearing in mind potential application to life support systems.

This paper has barely scratched the surface of the total problem; yet it has tried to cover the basic objects as broadly as possible in an effort to show what a truly complex and interdependent ecology man lives in. In so doing, it was necessary to give shallow treatment to some particular areas.

There is no question that long duration missions do seriously complicate the life support problem; as a result many unforeseeable and highly provoking situations will undoubtedly arise.

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Chapter 5

THERMAL CONTROL ANALYSIS OF OBJECTS ON THE LUNAR SURFACE

By

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During the past several years the Space Thermodynamics Branch of Research Projects Laboratory, Marshall Space Flight Center, has used a General Space Thermal Computer Program for providing thermal control analysis for many U. S. satellites. From onboard satellite measurements, thermal data have been obtained for comparison with theoretical calculations. The actual temperature curve of the satellites matched the theoretical curve with reasonable accuracy. Thermal control analysis was made on the flights of Explorers I, III, IV, VII, VIII, and XI, also Pioneers III and IV, the Balloon Satellite, Ionosphere Beacon Satellite, S-46 Satellite, and SA-5 dummy payload. At present thermal control analysis for the Pegasus Satellite is in progress.

In May 1963, a highly simplified computer program for analyzing the temperatures to be expected in a lunar shelter design was formulated and has been used for preliminary parameter studies. Figure 1 shows a cutaway view of the shelter, which is basically a cylinder having a radiator on top. The radiator, designated by (1), can be considered isothermal and non-operating for purposes of this analysis. Part (2) in the figure is the "internal point" and consists of a transmitter that sends data back to earth every hour, creating 10 watts of waste energy. Part (3) is the outer insulation of the shelter and part (4) is the inner wall structure; these two areas consist of an outer layer of superinsulation, a layer of aluminum, a layer of foam, and the inner layer of aluminum honeycomb. Part (5) is the floor of the shelter, which is fabricated from aluminum honeycomb. The base, part (6), is the landing pod of the Lunar Excursion Module. Part (7) is the lunar surface, and part (8) is the lunar subsurface of sufficient depth to be considered at a constant temperature. Figure 2 shows some of the temperatures that were derived from this computer program. A thorough presentation of the program is given in a report by Gierow [1].

In order to accomplish a complete thermal analysis, a much more sophisticated computer program will be required. Therefore, a general thermal control analysis program that can be applied to any shelter or vehicle configuration on or

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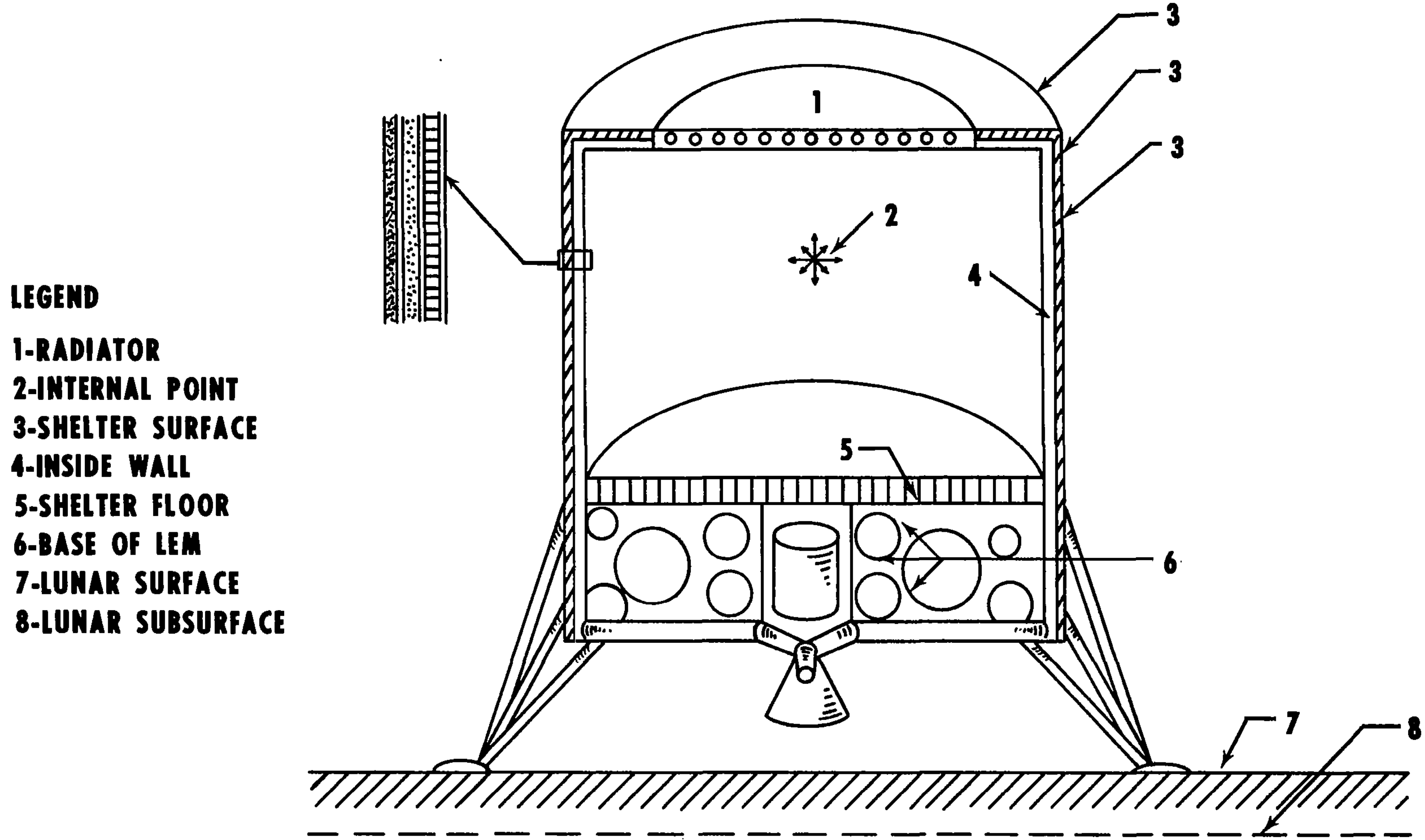


FIGURE 1. SIMPLIFIED LUNAR SHELTER FOR THERMAL ANALYSIS

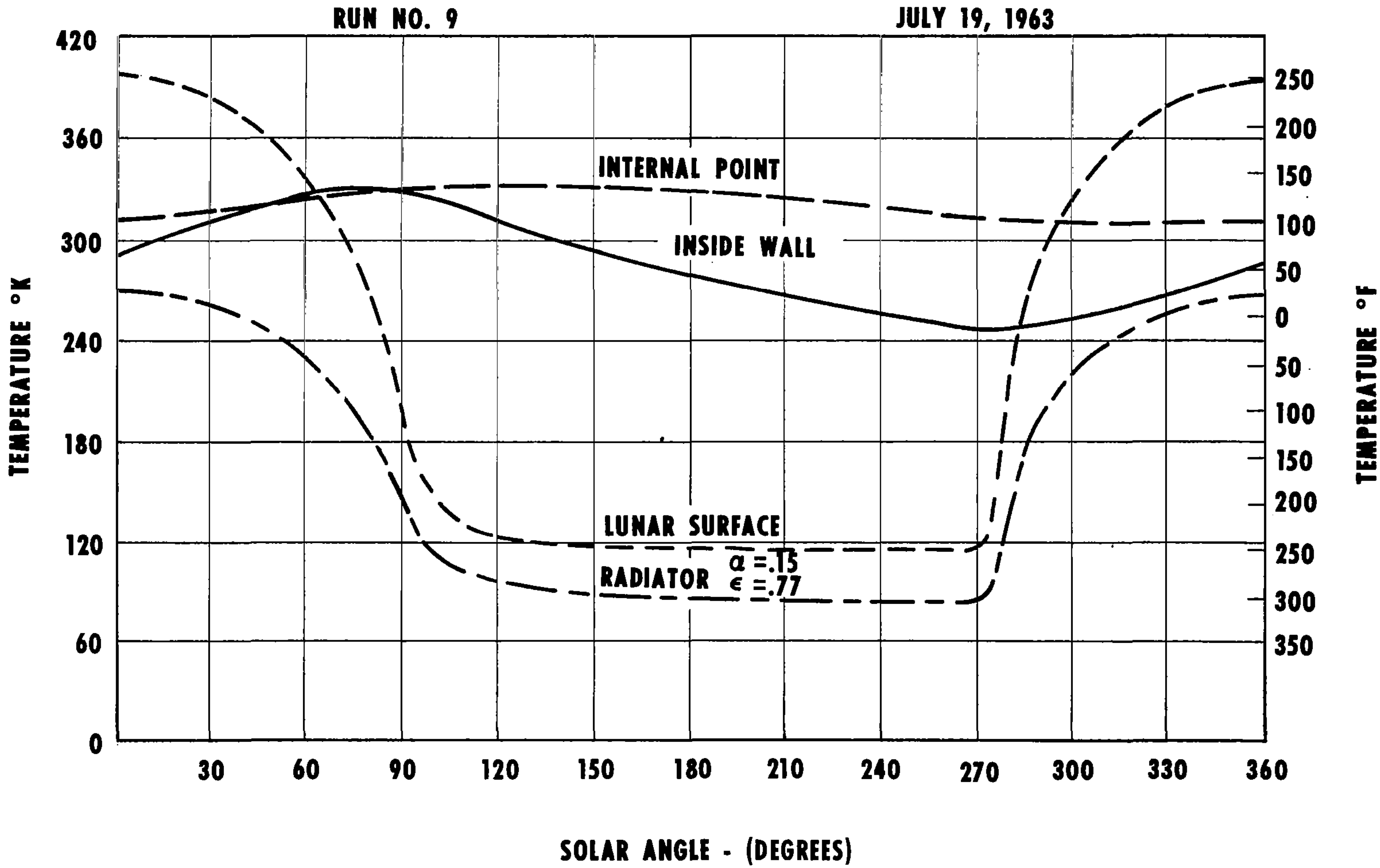


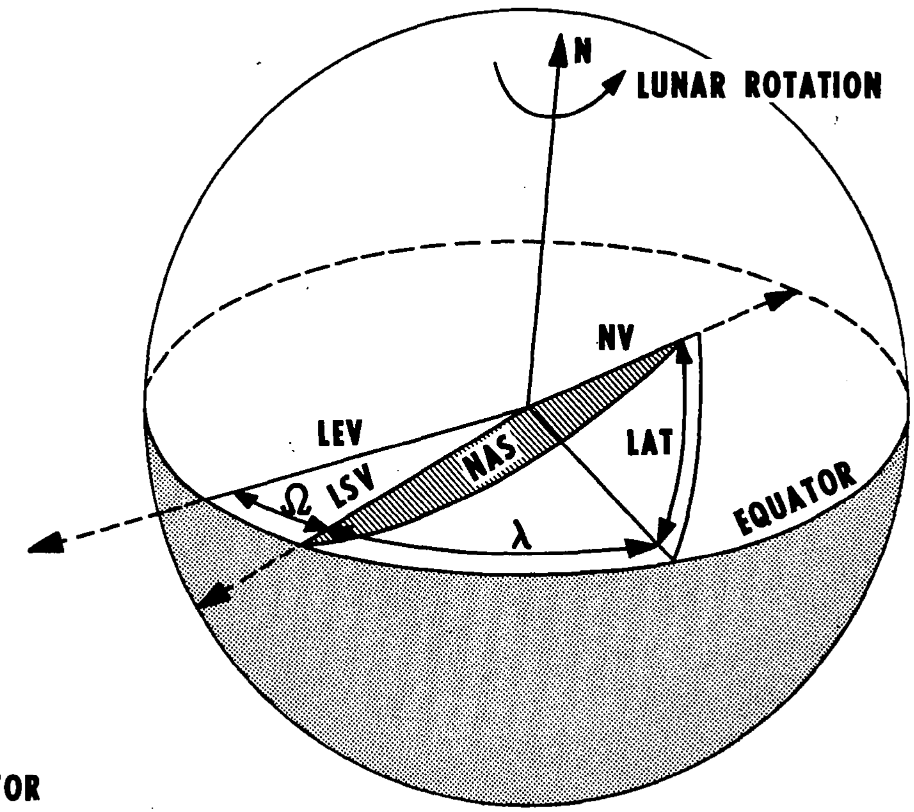
FIGURE 2. LUNAR SHELTER TEMPERATURES

below the lunar surface is being formulated. Analysis of this computer program, referred to as the General Lunar Thermal Program, is divided into four basic parts: (1) the orientation, (2) the thermal radiation input, (3) the basic heat flow diagram, and (4) the basic heat equation. Figure 3 is an orientation diagram in which the five-degree inclination of the moon's orbital plane to the ecliptic is initially disregarded. In this figure, the vector labeled "LSV" is a line passing through the center of the moon and the center of the sun, and lying in the moon's equatorial plane. All angles of longitude, or right ascension, are measured in an easterly direction from the intersection of this vector at the lunar surface and along the lunar equator. This intersection of the equator is the sub-solar point. The arc angle "λ" (lambda) is the longitude to shelter, and the arc angle "LAT" is the latitude to shelter. The arc angle "NAS" is the angle between the normal to the shelter and "LSV" or sun vector. This angle is of the utmost importance in determining the geometry factor for effective area calculations as will be explained later. Another vector of importance is the LEV (Lunar-Earth Vector), which always points towards the earth. Using the angle "Ω" (omega) and "λ" one can calculate the angle between LEV and the normal to shelter. This angle can be used to determine the shadowing of earth-oriented antennae or radiators.

Figure 4 depicts the main thermal radiation that a lunar shelter will experience. Solar radiation from the sun can be handled in the computer program in much the same manner as for satellites. The real problems are determining the thermal radiation from the lunar surface and reflected solar radiation. These quantities are variables dependent on the angle of incidence of solar radiation and viewing angle, for which highly accurate functions must be made available before a detailed thermal analysis can be achieved.

There are three major heat inputs to the lunar shelter (Fig. 5): (1) lunar albedo, or reflected solar radiation, (2) solar radiation, and (3) lunar thermal radiation. Heat conducted from the lunar surface or subsurface to the shelter is not shown on the diagram but is present in the computer program. The outside shelter surface radiates to outer space, and the inside experiences heat exchange between man (if present), shelter atmosphere, and shelter equipment. The excess heat in the shelter atmosphere and shelter equipment is dissipated through the radiator to outer space. In the simplified diagram (Fig. 5), it is impractical to illustrate the heat exchange which occurs between components of each block, i.e., man and his space suit, layers of space suit, layers of shelter wall, and various pieces of equipment. Consideration is also given to internal heat inputs that may vary with time, e.g., from a transmitter or human occupant.

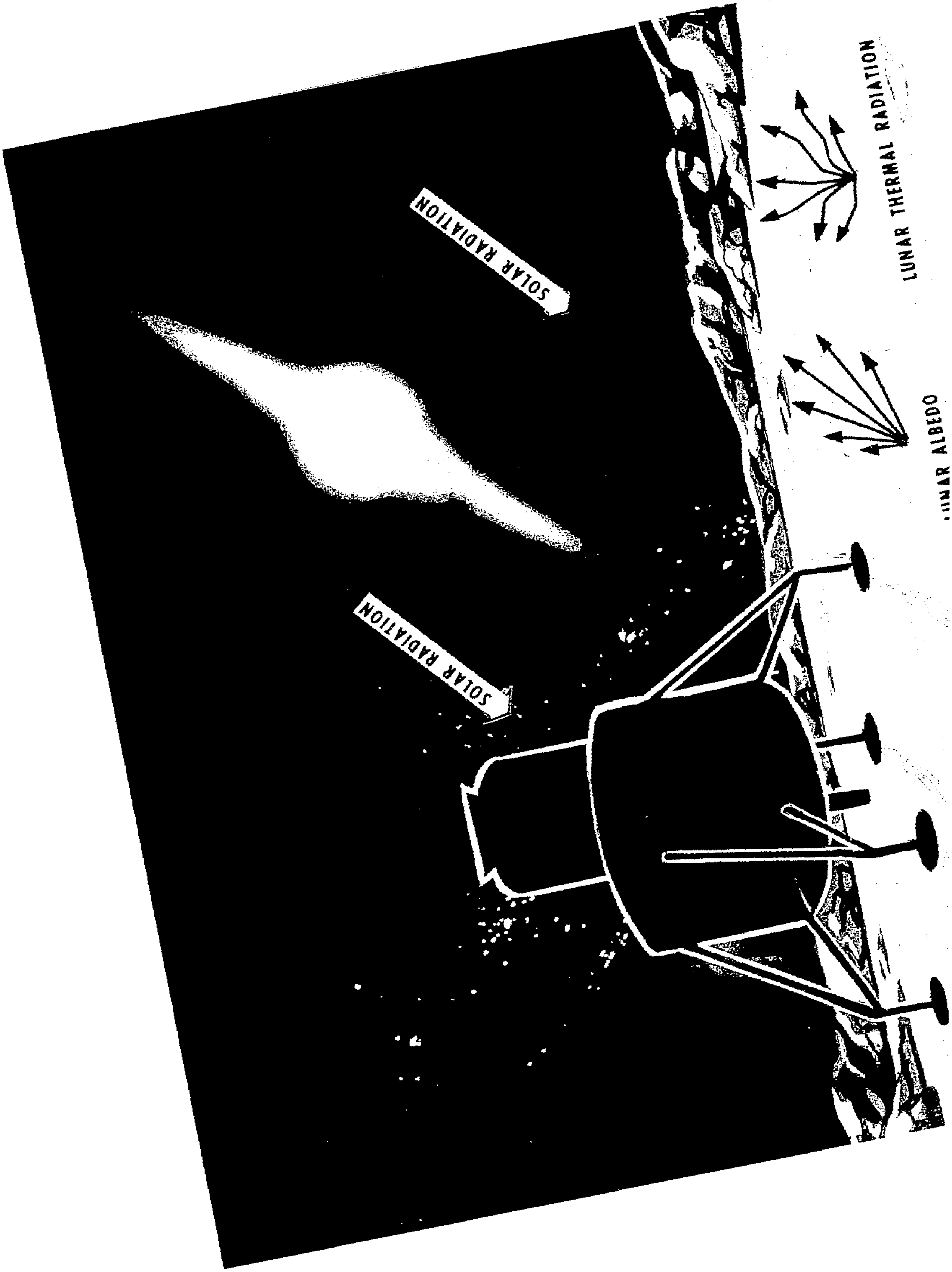
Figure 6 is a first order differential heat balance equation that is applied to each section of the lunar shelter, each section being considered isothermal.



LEGEND

LEV-LUNAR-EARTH VECTOR
LSV-LUNAR-SUN VECTOR
NV-NORMAL VECTOR
N-LUNAR NORTH POLE REFERENCE
NAS-NORMAL SUN ANGLE
λ-RIGHT ASCENSION
LAT-LATITUDE
Ω-SUN-EARTH ANGLE

FIGURE 3. LUNAR SHELTER ORIENTATION


SOLAR RADIATION
SOLAR RADIATION
LUNAR THERMAL RADIATION
UNAR ALBEDO

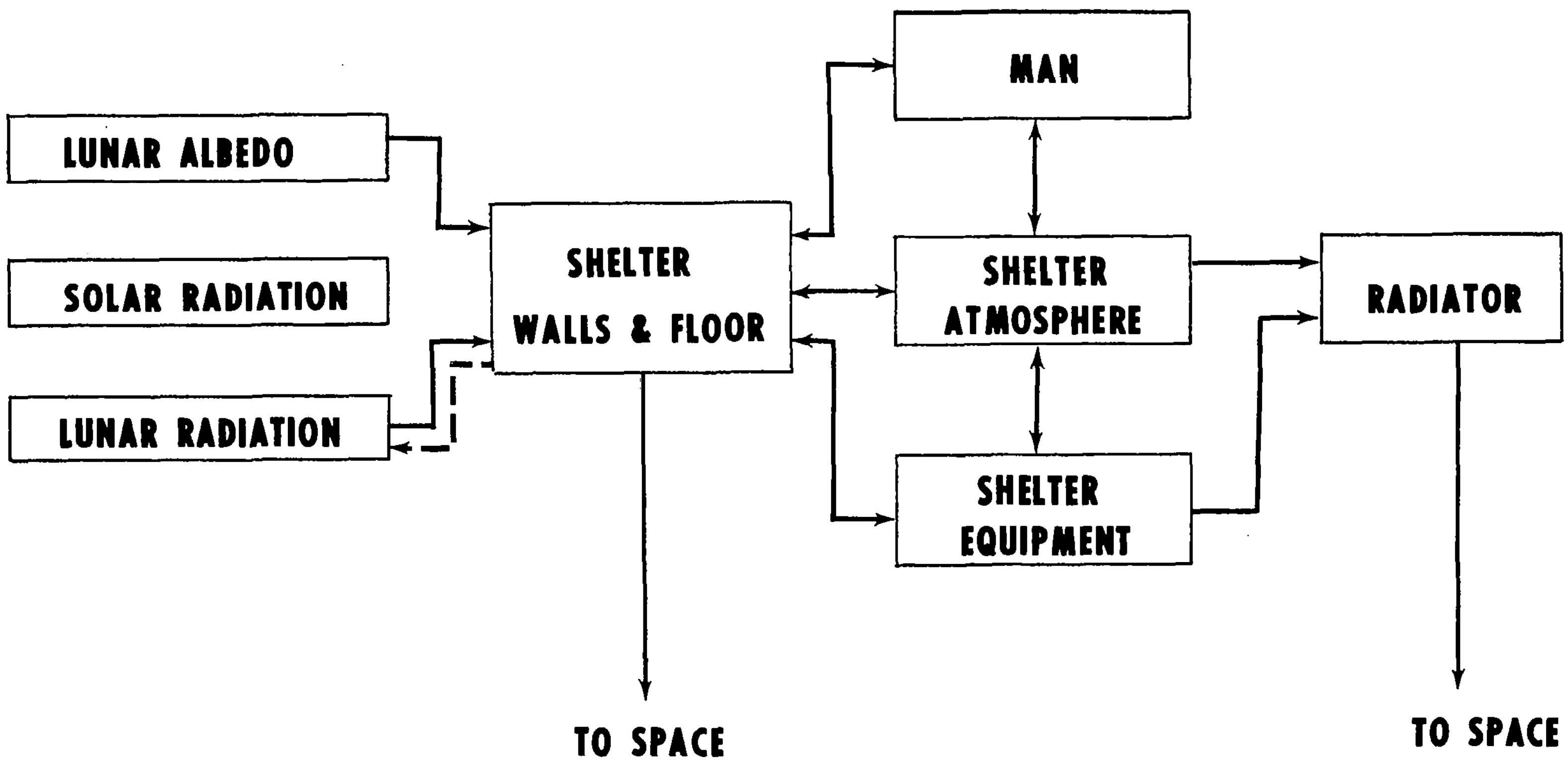


FIGURE 5. LUNAR SHELTER HEAT FLOW

$$\dot{T}_i H_i = A_{1i} \alpha_i S + A_{2i} \alpha_i B S + A_{3i} \epsilon_i E S + Q_i - A_{4i} \epsilon_i \sigma (T_i)^4 + \sum_{j=1}^{n} C_{ij} (T_j - T_i) + \sum_{j=1}^{n} R_{ij} \left[(T_j)^4 - (T_i)^4 \right] + \sum_{j=1}^{n} K_{ij} (T_j - T_i)$$

RATE OF HEAT FLOW	$\dot{T}_i H_i$
ABSORBED SOLAR RADIATION	$A_{1i} \alpha_i S$
ABSORBED LUNAR ALBEDO	$A_{2i} \alpha_i B S$
ABSORBED LUNAR THERMAL RADIATION	$A_{3i} \epsilon_i E S$
INTERNAL ENERGY GENERATED	Q_i
EMITTED SHELTER RADIATION	$(-) A_{4i} \epsilon_i \sigma (T_i)^4$
HEAT FLUX ABSORBED BY CONDUCTION	$\sum_{j=1}^{n} C_{ij} (T_j - T_i)$
HEAT FLUX ABSORBED BY RADIATION	$\sum_{j=1}^{n} R_{ij} \left[(T_j)^4 - (T_i)^4 \right]$
HEAT FLUX ABSORBED BY CONVECTION	$\sum_{j=1}^{n} K_{ij} (T_j - T_i)$

FIGURE 6. BASIC HEAT BALANCE EQUATION

In the past, the equation has been applied to as many as 22 isothermal sections on a satellite. In comparison, a lunar shelter, especially with a human occupant, will be divided into probably a hundred or more "isothermal" sections. In Figure 6, the first term is the rate of heat flow, the product of "$\dot{T}$" (rate of temperature change °K/hr) and H (heat capacity). The second term is the absorbed solar radiation term, a product of "A_{1i}" (effective area to solar radiation), "α" (absorptance to solar radiation), and "S" (solar flux at lunar surface). The third term is absorbed lunar albedo; it is a product of "A_{2i}" (effective area to lunar surface), "α" (absorptance of surface i), "B" (ratio of lunar reflected radiation to solar flux), and "S" (solar flux). The factor "B" is a variable depending on the surface being considered. As noted previously, a highly accurate function describing this factor must be available before a detailed thermal analysis can be achieved. The fourth term considered is the absorbed lunar thermal radiation; its first quantity, "A_{3i}," is the effective area of surface "i" to the lunar surface; the next quantity is "ϵ" (epsilon) or emittance of surface "i"; the next quantity is "E," the ratio of lunar thermal radiation to solar radiation; and as stated before, the last quantity "S" is the solar flux at lunar surface. Again we have a problem of determining a function to describe "E." It should be noted that "E" and "B" are dependent upon the same angles of incidence and viewing. The fifth term, "Q," the internal heat generated by section "i," may be a variable or constant (e. g., a transmitter that transmits only once a day or a generator or other device running constantly). The sixth term is the emitted shelter radiation, which is the product of "A" (radiating area to outer space), "ϵ" (emittance of area "i"), "σ" (Stefan-Boltzmann constant), and the fourth power of temperature of section "i" in °K. The seventh term is the heat flux absorbed by conduction from the surrounding sections; it is the product of "C" (conduction constant) and "$T_j - T_i$," the differences in temperature between areas "j" and "i." The eighth term is heat flux absorbed by radiation from surrounding sections; it is a product of "R" (radiation constant) and $(T_j^4 - T_i^4)$, the differences of the fourth powers of the temperatures of sections "j" and "i." The ninth, and last, term is the heat flux absorbed by convection currents; it is a product of "K_{ij}" (convection constant between fluid and surface) and $(T_j - T_i)$, differences in temperature between the surface and the fluid. One should realize that most of these terms are dependent upon shelter configuration including shapes, surface treatments, insulation and many other factors involved in calculating these constants of conduction, radiation and convection.

The "General Lunar Thermal Program" contains a variety of special subroutines that may be expanded to encompass many variables of importance to a thermal control analysis. The subroutines are divided into six major groupings:

(1) accuracy-rate variation

(2) earth orientation to lunar surface

(3) eclipse routine

(4) lunar temperature

(5) geometry factors and effective areas

(6) thermal characteristics of materials

The first subroutines to be considered are those concerning the accuracy and rate at which the computer program is to be run. These subroutines prevent the solution obtained by the Runge-Kutta Fourth Order numerical method for a first order differential heat balance equation from experiencing numerical instability and giving erroneous answers. This numerical instability occurs when a sudden and sharp change in temperature results in an extremely large temperature difference over the increment of time taken. Normally, the computing procedure would try to correct this large change by entering a large change in the opposite direction. This would result in an expanding error that would soon reach the computer limit and shut the computer off. The accuracy rate variation subroutine prevents this from occurring by decreasing the time increment that is taken when the temperature slope or change becomes steep or abrupt. Also, when temperature change is practically constant, or a low degree of a slope occurs, a larger time increment is taken to save computation time and money.

The subroutine determining earth orientation to the lunar surface is vital in that a lunar shelter or vehicle having a dish antenna, or some other movable device that is earth-orientated, will at all times require a knowledge of the exact location of the earth will respect to the lunar shelter or vehicle. By knowing the location of the earth with respect to the normal to the moon's surface, as related to the shelter or vehicle, one can determine the direction in which the dish antenna or other device is pointing. Also, as described in the orientation diagram, the angle between the normal to lunar surface and the sun vector can be calculated; therefore, by knowing these two angles and their relationships, the shadowing effect and effective area of the dish antenna or other device can be determined. If the earth orientation is known, one can determine when the vehicle is in "line of sight" and, therefore, when transmitters are operating as internal heat generators. In determining the angle between the normal to the lunar surface and the earth, the five-degree inclination of the moon's orbital plane to the ecliptic is initially neglected. Therefore, the earth's and moon's orbits are assumed to lie in the same plane. The only input needed in the computer program to determine the angle between the normal and the earth is the latitude and longitude of the lunar object at full moon.

Another subroutine that should prove to be both interesting and valuable is that for lunar eclipses. During the period between 1964 and 1973, there will be a total of 14 lunar eclipses [2]. In five of these, the moon will pass only through the penumbra and a partial eclipse will occur. The other nine will be in the umbra and will be total eclipses. The longest total eclipse will occur in 1971 and will last for 102 minutes (1.7 hours). The longest partial eclipse will occur also in 1971 and will be 224 minutes (3.7 hours) long. The shortest partial eclipse lasts almost an hour (52 min.). From these figures, it would be interesting to determine the effect on the temperature of a lunar shelter or vehicle if it were on the lunar surface during an eclipse, especially if the shelter was using passive thermal control, or an active thermal control system not functioning at this time.

The temperature of the lunar surface is not constant but varies with moon rotation and with physical surface characteristics. At present, there is a subroutine that determines the temperature variation of a lunar surface and subsurface. In this mode, the surface and subsurface are divided into homogeneous isothermal layers. The new subroutine will contain this thermal model plus a choice of several others to be determined by the location of the shelter on the lunar surface.

As in the General Space Thermal Program for satellites, the General Lunar Thermal Program will contain a group of subroutines for determining geometry factors and effective areas. These two are related in that the effective areas, say, to solar radiation, are equivalent to the geometry factor multiplied by the area of the surface exposed to radiation. The geometry factor in the case of solar radiation is dependent upon the angle between a specific surface and the sun. Since this angle constantly changes as the moon rotates, the geometry factor must be calculated for each increment of angle that is used in computation. Also, the geometry factor is dependent upon the geometry of the surface (i.e., if it is curved, flat, cylindrical, or conical). Consideration will also be given to shadowing effects from other areas, and possible dust layers on the shelter surface. Another series of geometry factors will have to be determined for areas exposed to lunar radiation and lunar albedo (reflected solar radiation). This group of subroutines constitutes a good portion of the computer program.

The last group of subroutines contains thermal characteristics of materials. Maximum use will be made of data and research from the Research Projects Laboratory of MSFC and other NASA centers in these subroutines. Physical characteristics that vary with temperature, such as thermal conduction, thermal contact resistance, heat capacity, reflectance, emittance and solar absorptance, will be set up in subroutines. This procedure will provide a very accurate picture of temperatures to be expected in a lunar shelter. It will also provide a simple means of introducing new methods of semi-active thermal control surface techniques in the program. An example is a shutter-type device whose absorptance and emittance change with temperature as shutters are opened or closed.

It is expected that this computer program will be extremely useful in performing thermal control analysis of objects on the lunar surface. However, before such an analysis can be performed for a particular design, a complete and detailed breakdown of the thermal characteristics of the specific object is required. This breakdown includes the determination of constants such as absorptance, emittance, radiation, conduction, and convection. There is no simple procedure for determining these constants; it demands a thorough understanding of the physics of heat transfer and of the physics of the moon.

REFERENCES

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