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ANNUAL REPORT
to the
National Aeronautics and Space Administration
for
STUDIES RELATED TO THE SURFACES OF THE MOON AND PLANETS

NASA Grant NGL 39-011-085
for the period
April 1, 1973-March 31, 1974

Principal Investigator
Bruce Hapke

I. RESEARCH ACCOMPLISHED

This report is a summary of the research performed under NASA grant NGL 39-011-085 for studies related to the surfaces of the moon and planets during the period April 1, 1974 - March 31, 1975. The research projects continued during this time included studies of the transmission and reflection spectra of silicate minerals, glasses and films, correlated with analyses of these materials by various methods.

This has been an extremely fruitful period in terms of achieving an understanding of the various mechanisms which can cause absorption of light in lunar soil. We have prepared a variety of glasses of lunar composition with different amounts of Fe and Ti under both reducing and oxidizing conditions, and also by sputter-deposition and thermal evaporation and condensation. These materials were then analyzed by wet chemical, electron microprobe, ESR, Mossbauer and magnetic methods.

These studies established that the sputtered and evaporated films are dark because they contain superparamagnetic Fe, that is, metallic Fe in grains of size 100 Å. These Fe grains also exhibit the so-called ESR "characteristic resonance" at g-2.1. The factor by which various elements are enriched in the sputtered films over the parent glasses was found to be correlated with atomic weight, except for Na and K. Thus, by assuming that the lunar regolith contains a few per cent of materials which were deposited from a vapor generated either by sputtering by the solar wind or thermally evaporated by micro-meteorite impacts we can account in a natural manner for several heretofore puzzling optical, chemical, and magnetic properties of the soil. As a result of the study of the glasses melted in vacuum we are able to identify with confidence the features in the ratio spectra of various lunar areas obtained by McCord and his co-workers. The fractionation produced by sputter-deposition is a new process which has not been proposed before. It may be of considerable importance to early chemical fractionation in the solar nebula as well as in the lunar soil.

These results are discussed in detail in a preliminary fashion in two pre-prints which are included as part of this report. These papers were given at two meetings and have been accepted for publication (see Section II).

II. MEETINGS AND PUBLICATIONS

William Cassidy attended the Conference on Planetary Satellites, Ithaca, N.Y., Aug. 1974 where he delivered a paper by William Cassidy and Bruce Hapke entitled "Effects of Darkening Processes on Surface Soils of Airless Bodies." This paper has been accepted for publication in *Icarus*.

Bruce Hapke attended the Conference on the Lunar Regolith, Houston, Texas, Nov., 1974, where he delivered a paper by Bruce Hapke, William Cassidy and Ed Wells entitled "Effects of Vapor-Phase Deposition Processes on the Optical, Chemical and Magnetic Properties of the Lunar Regolith." This paper has been accepted for publication in *The Moon*.

III. PERSONNEL

The following persons were partially supported by this grant:

B. Hapke, principal investigator	15%
W. Cassidy, co investigator	15%
E. Wells, graduate student research assistant	50%
E. Baier, graduate student research assistant	50%
L. Tepper, graduate student research assistant	50%
L. Trucano, secretary	25%

EFFECTS OF DARKENING PROCESSES ON SURFACES OF AIRLESS BODIES

ABSTRACT

We find the lunar darkening process could be due neither to simple addition of impact-melted glass nor to addition of devitrified glass to crushed lunar rock. There is evidence that lunar soil grains have thin, very light-absorbing coatings that mask absorption bands, seen in the reflection spectra of freshly crushed lunar rock, in the same manner as they are masked in the spectra of lunar soils. We believe the processes that produce these coatings are (1) deposition of atoms sputtered from lunar soil grains by solar wind particles and (2) deposition of vapor species vaporized from lunar soil grains by micrometeorite impacts. Coatings produced in laboratory simulations of these processes owe their strong light-absorbing properties in large part to the presence of abundant metallic Fe grains smaller than 100Å in diameter. Another process, which depends on implantation of solar wind protons in lunar soil grains and their later mobilization during micrometeorite impacts to produce metallic Fe in the impact glass, also seems reasonable but has not yet been demonstrated experimentally. As a result of impact vaporization the moon would preferentially lose minor amounts of light elements, principally monatomic oxygen, and this would result in oxygen depletion in the vapor condensate. This type of fractionation would be more extreme on airless bodies with lower escape velocities. Sputtering occurs at higher effective temperatures and this would cause loss of all common rock-forming elements in approximately equal amounts. There would

be some bias in this process toward retention of very heavy trace elements - a characteristic that has been observed in the lunar soil. This bias would be less important for smaller airless bodies. We describe an apparent new type of fractionation that occurs during deposition of sputtered atoms. This fractionation favors retention of higher mass atoms over lower mass atoms, and appears to be a linear function of mass. This may explain observed isotopic fractionations in lunar soil, in which the heavier isotope always appears to be enriched relative to the lighter one. This "first bounce fractionation" process should operate on all airless bodies. Na and K apparently do not conform to this fractionation process and have a much greater tendency to escape. This may help explain the presence of high Na concentrations around Io.

EFFECTS OF DARKENING PROCESSES ON SURFACES OF AIRLESS BODIES

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REVIEW

Questions involving surface processes on bodies without atmospheres have been most intensively discussed with relation to the moon. Since rays from newer craters are bright and rays from older craters are progressively darker with age, it is recognized that some darkening process or group of processes acts very slowly through time on the lunar surface (Gold, 1955; Hapke, 1970).

Explanations offered to account for this darkening process include, among others, the production of glass at the lunar surface (Conel and Nash, 1970; Adams and McCord, 1971). According to this reasoning, while crushed lunar rock has a relatively high albedo glass produced by impact melting of crystalline rock is quite dark; therefore as time passes more and more dark glass is mixed into or deposited upon light-colored surface sediments and they become progressively darker. We have found (Hapke, et al., 1973) that true glasses of lunar composition produced in the laboratory have an albedo much higher than that of lunar soil, therefore a mixture of such glasses with pulverized lunar crystalline rocks could not duplicate the degree of darkening evident in lunar soils (Figure 1). Unfortunately it is easy for even very careful workers to be led astray in the laboratory production of simulated lunar glass and to conclude that lunar glasses would be highly absorbing. Glass of lunar composition is very dark, for example, if it contains too much ferric iron; this can happen in a number of ways. Nitrogen used as a furnace atmosphere, even when of guaranteed high purity, may contain unacceptable levels of oxygen contration or water vapor. Platinum crucibles can also produce concentrations of Fe^{3+} that are too high, even in a well-controlled atmosphere. The reason for this is that metallic Fe alloys very readily with platinum, therefore Fe^{2+} present in a melt will dissociate as follows: $3Fe^{2+} \rightarrow Fe^{0} + 2Fe^{3+}$. The Fe^{0} then alloys with the platinum container, is removed from the melt, and causes the reaction to continue to the right with further production of Fe^{3+}.

In our experimental work we produced glasses in graphite crucibles in Vacuum and in a nitrogen atmosphere. The graphite scavenges excess oxygen, and metallic iron produced does not alloy with the crucible; we try to ensure that the resulting glass has been equilibrated in the presence of a small amount of metallic iron, comparable to the small amounts noted in lunar soils and rocks. Our results indicate that both crushed lunar rocks and glasses produced in the described way would have to be made darker by some other process if they were to approach the low reflectivity of lunar fines.

Partial devitrification could make glasses more absorbing by crystallization of opaque inclusions (Hapke, et al., 1973; Nash and Conel, 1973). Many so-called glasses made in the laboratory are probably much darker because they have undergone devitrification during cooling. Degree of devitrification is a complex function of rate of cooling and composition of glass. Nash and Conel (1973) feel it is unlikely that glass of lunar basaltic composition produced by micrometeorite impacts would cool slowly enough to devitrify to any significant degree. On the other hand, black glass spherules at the lunar surface often show extensive devitrification. Furthermore, devitrification would undoubtedly occur if hot material from an ejecta blanket covered surface glass and reheated it. Presumably fresh glass within a thick ejecta blanket would also cool slowly enough to devitrify and later be brought to the surface by gardening processes. It is not known whether such ejecta blankets would be hot or not, although the higher metamorphic grades of breccia have apparently been heated (Warner, 1972) and some breccias apparently have been reheated (Chao, et al., 1972). Assuming the described process is feasible, some degree of darkening of surface materials might eventually occur. Devitrified laboratory glasses, however, have absorption bands characteristic of ilmenite which are not visible in lunar fines and which would have to be masked during the course of lunar soil darkening. In addition, the idea that subsurface sediments contain large quantities of darker, devitrified grains working their way upward is not supported by examination of core samples. For these reasons we do not feel the recrystallization process is an important one for lunar darkening.

Our approach to the question of darkening (Hapke, et al., 1970) has been to consider the effects of two weathering processes that occur only on bodies without atmospheres: (1) thermal vaporization by micrometeorite impact, followed by vapor-solid condensation on nearby surfaces and (2) sputter-vaporization by solar wind particles, followed by vapor-solid condensation on nearby surfaces. According to laboratory simulations (Gault, et al., 1972), impacts of micrometeorites cause nearly as much vaporization as melting of target material. Our laboratory simulations have shown that if this vaporized material condenses on a nearby ~~grains~~ surface it forms a thin, absorbing deposit~~s~~ which tends to darken all the light-colored grains and mask any absorption bands, such as the characteristic one-micron band of ferrous iron. A similar effect is observed due to sputter-vaporization followed by deposition (Fig. 2).

In a series of experiments (Hapke, et al., 1970) we have shown that chemical etching of dark lunar soil removes material at grain surfaces and restores the soil to a condition of high reflectivity characteristic of crushed lunar basalt. The soil can then be returned to a condition of low reflectivity by either of the processes described above. We have concluded, therefore, that darkened lunar fines have been coated by light-absorbing thin films produced by one or both of these processes, and that this can account for at least part of the lunar darkening effect. Gold, et al. (1974, in press) have recently reported auger electron studies of the smoothed surfaces of lunar fines samples in which they found overall enrichments in iron at the grain surfaces, compared to the bulk compositions of the grain samples. The degree of enrichment is correlated with the albedo of the fines. We consider this to be definitive proof of the existence of iron-enriched coatings on the lunar soil grains.

There is the further question of why these deposits are so light-absorbing. Lunar fines (10084) and pulverized crystalline rock (10017) were heated in an oxygen atmosphere to 100°C on a thermogravimetric balance. Weight of the fines increased by 2%, whereas the rock powder gained only 1%. If all metallic Fe and Fe^{2+} in the samples (according to published analyses) were oxidized to Fe^{3+}, both weight gains would have been about 1%. The excess weight gain of the fines could be explained by oxidation of sub-microscopic metallic Fe in vapor-deposited films. Further, some electron microprobe analyses of the surfaces of five grains, hand-picked as probably being coated, in which we compared the weakly penetrating induced L_α iron radiation to the strongly penetrating induced K_α iron radiation, showed qualitatively that iron was enriched at the very surfaces of four of the five grains (Hapke, et al., 1970).

In an attempt to further characterize the thin films, magnetization curves of several artificial glasses of approximate Apollo 11 composition (∿15% FeO) were measured. In such a curve the high-field susceptibility χ is proportional to the paramagnetic (i.e., Fe^{2+}) plus ~~and~~ superparamagnetic iron content (i.e., metallic Fe in grains smaller that 100Å) while the induced remanence $I_s(0)$ is a measure of the amount of metallic Fe in the form of single- and multidomain particles. These ordinary glasses had $\chi \sim 2.3 \times 10^{-5}$ emu/gm and $I_s(0) \sim .04$ emu/gm, consistent with FeO = 14% and metallic Fe ∿.02%. Evaporated films, however, had $\chi \sim 36 \times 10^{-5}$ and $I_s(0) \sim 0.1$; this large value of χ would require an FeO content of more than 200%. This result can only be accounted for if most of the iron in the films is in the form of superparamagnetic particles. A detailed analysis (Hapke, et al., in preparation) indicates the films contain >10% iron as superparamagnetic particles smaller than 30Å. Thus, these films are effective darkening agents because they contain abundant submicroscopic inclusions, probably of metallic iron. We feel that at least part of the lunar darkening process is caused by the presence of this type of material, both on the surfaces of loose grains and disseminated through agglutinate material by assimilation of coated fines.

Housley and his colleagues (1973; 1974) have recently pointed out that solar wind protons imbedded in the surfaces of lunar grains (Lord, 1968) may become the agents of another darkening process by reducing ferrous iron to metallic iron when the hydrogen-enriched grains are melted by micrometeorite impacts. This process had not occurred to us, but it seems an eminently reasonable suggestion because it would produce a glassy matrix with submicroscopic inclusions of metallic iron. This hypothesis, however, has not been verified experimentally.

As a result of the lunar research discussed above we now believe there are at least four processes that are capable of producing slow darkening at the surfaces of silicate bodies without atmospheres: (1) devitrification by reheating of glass may play a role, but probably more important are (2) vapor-deposition from micrometeorite impact, (3) vapor-deposition from solar wind sputtering, and (4) production of submicroscopic iron particles in glass whose source material contained solar-wind-imbedded hydrogen before impact by a micrometeorite. Aside from devitrification by reheating, which depends on impacts by large meteorites, all methods of darkening the lunar surface depend on solar wind particle bombardment, micrometeorite impact, or both. These are processes that do not occur on the earth's surface and it would be easy to overlook them or minimize their importance when considering surface processes on airless bodies. All these processes change the reflectivity of the lunar surface and effectively mask the characteristic absorption bands of multivalent cations which would otherwise be useful indicators of chemical composition in the reflection spectra.

Some of these processes may also produce chemical fractionation of surface materials, raising the possibility of misinterpretation of data obtained by study exclusively of surface materials by remote sensing devices. In the following sections we examine the fractionation effects these processes might have on the surface materials of airless bodies and try to assess the relative importance of these processes on bodies other than the moon.

FRACTIONATION EFFECTS

The single effect common to the lunar-darkening mechanisms of micrometeorite impact and solar wind particle bombardment is that they instantaneously impart a large amount of energy to a small volume. In the case of micrometeorite impact the energy is distributed within a single large grain or over a number of smaller grains. This produces comminution, melting and vaporization, as well as release of any solar wind gas particles that had previously become imbedded in grain surfaces. In the case of solar wind particle bombardment the energy release is effective over an even smaller volume. This produces sputtering of the surface atoms of grains which, because it involves energies much greater than chemical bonding energies, can be thought of as a nonequilibrium vaporization at effective temperatures of tens of thousands of degrees. An accompanying effect may be the disorganization of crystal structure taking place below the sputtering erosion surface as the solar wind particles expend their remaining kinetic energy and come to rest. This may produce the amorphous grain borders discussed by Dran, et al., (1970); Borg et al. (1970); and Borg et al. (1971).

Because impact vaporization occurs at temperatures close to those for chemical equilibrium between vapor and liquid, the liquid would tend preferentially to lose those species with higher vapor pressures (i.e., vapor fractionation). Because velocities of the vaporized species depend on their masses, larger fractions of the velocity distribution curves for light species will extend past lunar escape velocity and this will result in some relative depletion of the lunar surface in these lighter species, principally monatomic oxygen, but also of lesser amounts of Na, Mg, and Al (Fig. 3 and Table 1). This will result in other grains at the lunar surface receiving coatings of condensed material that have been notably depleted in O and relatively enriched in heavier elements. While there would be only a small net loss of material from the moon, the effect would be greater for smaller satellites with lower escape velocities.

Wehner, et al. (1963) point out that a large fraction of all sputtered atoms would leave the lunar surface at greater than escape velocity; therefore he calculates that the moon may have lost as much as a 17 cm-thick layer during 4.5 aeons. Because the sputtering mechanism operates only on atoms very close to the surface of a grain, material lost in this way probably would not have been fractionated upon leaving the grain surface. On the other hand, velocity distribution curves, calculated on the assumption of an effective Maxwellian distribution, suggest that for temperatures in the range 10,000°-50,000°, considered to be the effective temperature range of sputtered atoms, there would be some preferential retention of heavy elements on the moon, (Figures 4 and 5; Table 2).

¶ Except possibly in the case of oxygen, neither of these processes seems adequate to produce more than slight fractionation effects on the moon. Our experiments, however, suggest there is a more extreme type of fractionation that has not been described previously: apparently those sputtered atoms that happened to first strike an adjacent grain surface instead of immediately escaping from the moon would undergo a significant fractionation process that depends on their sticking coefficient at the grain surface. The sticking coefficient, in turn, may depend directly on the mass and inversely on the velocity of the sputtered atom. For example, if a sputtered oxygen atom and a sputtered iron atom strike the same surface either with equal momenta or kinetic energies the oxygen atom will strike with several times the velocity of the iron atom and will tend to rebound more readily. Because of this more oxygen than iron atoms will get a second chance to escape the moon. The vaporization and sputtering processes are shown schematically in Figures 6 and 7. This proposed fractionation mechanism is supported by the fact that experimentally produced sputter films are richer in heavy elements than the parent by a factor that depends on their masses (Figures 8 and 9).

Of the common rock-forming elements, then, iron and titanium are enriched over lighter elements in the sputter-deposited films, while elements such as oxygen are depleted. Oxygen deficiency and Fe + Ti enrichment would produce very light-absorbing films.

One wonders if there is any evidence in the lunar samples to support belief in a novel process that favors fractionation of elements solely according to their mass, with no effect that can be ascribed to their chemical properties. It might be suggested that the five-fold enrichment of metallic iron in lunar fines over lunar basalts (Pearce and Simonds, 1974) could be due to such a process. However, the total iron in the fines seems to be lower than in associated crystalline rocks. Keays, et al., 1970; Ganapathy, et al., 1970; and Laul, et al., 1971 have noted significant enrichments of such heavy trace elements as Ir, Au, Zn, Cd, Ag, Bi, Tl, Br, Te, Se, Ga, Rb, Cs, and In in lunar soils. They have sought to attribute these enrichments solely to the meteoritic increment, with some degree of success, concluding that the enrichment ratios somewhat resemble primordial material (i.e., carbonaceous chondrites).

Undoubtedly the moon has received its share of carbonaceous chondrite material, as well as material representing other classes of meteorite. Some of the observed enrichment in heavy elements, however, may have resulted from the fractionation process we describe above which we propose to call first bounce fractionation. An alternative interpretation of the data might be that both the lunar surface and carbonaceous chondrites have been exposed to the same sputter-fractionation process, causing heavy-element enrichment in both. This proposition may not survive quantitative examination.

Perhaps a better indication of mass-dependent fractionation in lunar soils is the observation that light isotopes of C, O, Si, S, and K are anomalously depleted in lunar soils relative to their heavier isotopes (Epstein and Taylor, 1971; Grossman, et al., 1974; and Clayton et al., 1974). This is not true of lunar rocks, whose interiors have not been subjected to the postulated first bounce fractionation process.

One can readily see that if this fractionation process has caused detectable isotopic fractionation in bulk lunar soils it is because thin films coating the soil grains are significantly enriched in the heavier of the isotopes, and the anomalous material is in reality the thin film. Isotopic analysis of material leached from soil grains should therefore show even greater evidence of isotope fractionation.

Another interesting conclusion, based on Figures 8 and 9, is that both Na and K, once sputtered, have very low sticking coefficients and do not recondense in accordance with the mass regularity we have noted for other sputtered elements.

no ¶

Relative to other elements, our data suggest that as a result of sputtering a 3-fold to 6-fold anomalous enrichment in Na, and perhaps a hundred-fold anomalous enrichment in K would occur over an airless body. This may help explain the recent discovery (Brown, 1973) of Na in the atmosphere of Io. K should also be searched for. Because Na (and K if found) is so easily liberated by sputtering, its high concentration in the atmosphere of Io may not be representative of its concentration in surface materials.

RELATIVE EFFECTIVENESS OF THE SUGGESTED SURFACE PROCESSES

As we have seen, both micrometeorite impact effects and effects due to solar wind proton bombardment are indicated on the moon and would produce coatings on grain surfaces. Presumably these processes would also operate on Mercury, since the magnetic field of the planet is only marginally able to stand off the solar wind, and micrometeorites would be moving faster at that distance from the sun. Moving out from the sun, however, the solar proton flux decreases rapidly, and is apparently 100 times lower at the distance of Jupiter than at 1 A.U. (Wolfe, et al., 1974). For a static surface where gardening processes are not considered, equilibrium between production of thin films and resputtering of them is estimated to be reached on the moon in 10^5 years (Hapke, 1973). With the flux 100 times lower at Jupiter this equilibrium might be reached in 10^7 years.

Jupiter satellites within the Jovian magnetosphere would be protected from the solar wind flux; this would include satellites 1-5. Stable zones of trapped particles have been detected inside 20 Jupiter radii on the sunlit side, however, and these might produce effects similar to the solar wind. Most affected by this would be Satellite 5, which occupies an orbit within this distance from Jupiter. The radiation fields extend much farther out on the night side, however, and probably include satellites out to about Callisto. Any of these satellites that had no atmosphere could then show effects of proton bombardment.

If we assume the source of micrometeorites to be the asteriod belt, then impacts on asteroids by micrometeorites occupying orbits in that region would be less important because of low relative velocities. Micrometeorites that have planet-crossing trajectories, however, could have aphelia extending out at least to 10A.U. and could take part in vapor-producing impact events. Harwit (1964) pointed out that adequate sources of dust to maintain the zodiacal cloud against the Poynting-Robertson loss rate are not obviously present. He proposed that the cloud is replenished constantly by primordial dust grains that never became incorporated into comets and that still occupy long-period cometary orbits. Such dust grains, if they exist, undoubtedly cause micrometeorite impacts on all airless bodies in the solar system.

We also conclude that very small airless bodies will be chemically fractionated at their surfaces not only by first bounce fractionation but also significantly by impact-vaporization fractionation.

A special case of vaporization fractionation might occur with a mechanical mixture of ice and refractory grains, as has been suggested for the makeup of comets and for some of the satellites of the major planets (Lewis, 1971). If bombardment by micrometeorites occurred, and the body were relatively small, preferential vaporization loss of ice could occur leaving a residual concentration of refractory grains at the surface. The same process could cause production of hydrogen-deficient ices at the surface. These effects could change its appearance considerably and could lead to wrong ideas about its bulk composition. If the surface of Iapetus had previously been darkened in this manner, a relatively large meteorite impact or a large number of smaller impacts occurring preferentially on one face of the satellite would expose underlying light-colored material in the same manner as that of a fresh ray crater on the moon or Mercury.

We have attempted to show that proton bombardment sputtering and micrometeorite impact vaporization are factors that must be considered for all airless bodies in the solar system. We conclude that neglect of the effects of these processes might cause the bulk compositions of such bodies to be wrongly estimated from remote sensing methods. Since mass-dependent fractionation is involved, we also conclude that neglect of the effects of these processes might cause the bulk-elemental and bulk-isotopic compositions of such bodies to be wrongly estimated even from analyzed samples of soils from these bodies.

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Table 1: lunar fractionation of vaporized species at 3000° K. A Maxwellian distribution of speeds is assumed, of which half will have a net downward component. Calculations given are for those vapor species found to be most common over vaporized lunar samples (De Maria, et al., 1971). The assumed vaporization temperature of 3000° K is probably too high, therefore estimates of fractions lost should be considered upper limits.

Vapor species	R.M.S. speed (km/sec)	Percent >2.4 km/sec	Probable fraction lost (%)
O	2.16	28.5	14.25
Na	1.81	15.6	7.8
Mg	1.36	13.8	6.9
Al	1.67	11.2	5.6
O_2	1.53	7.0	3.5
K	1.38	3.0	1.5
Ca	1.37	2.8	1.4
SiO	1.30	1.6	0.8
Fe	1.16	0.8	0.4
TiO	1.08	0.2	0.1
TiO_2	0.97	~ 0	0

Table 2: lunar fractionation of sputtered atoms at effective temperatures of 10,000° K (low values) and 50,000° K (high values). Effective Maxwellian distribution of speeds is assumed, of which an unknown fraction would have a net downward direction, because of sputtering from sides of grains, and would be more susceptible to redeposition instead of loss from the moon.

Sputtered atoms	R.M.S. speed (km/sec)	Percent >2.4 km/sec
O	3.95 - 8.84	77.8 - 97.2
Na	3.30 - 7.37	65.9 - 95.4
Mg	3.21 - 7.17	63.8 - 95.0
Al	3.04 - 6.80	59.6 - 94.4
Si	2.98 - 6.67	57.8 - 94.0
K	2.53 - 5.65	43.6 - 90.8
Ca	2.50 - 5.58	42.4 - 90.4
Ti	2.28 - 5.11	34.4 - 87.6
Fe	2.12 - 4.73	28.2 - 85.0

FIGURE CAPTIONS

Figure 1. Reflectivity spectra of lunar fines (10084 $<$37 microns), crushed lunar rock (10022), lunar rock (10022) melted in vacuum, quenched to a glass and crushed, and lunar rock (10022) melted in air, quenched to a glass and crushed. These runs were carried out to determine if glass made under "lunar" conditions from lunar rock could be mixed with crushed, unheated lunar rock to duplicate the spectrum of the fines. The glass made in vacuum had too high an albedo to accomplish this, and also displays a broad absorption band due to ferrous iron. Glass made under non-lunar oxidizing conditions was dark enough, but still displays the ferrous iron absorption band.

Figure 2. Transmission spectra of a sputter-deposited and a vaporization-deposited thin film. Parent material was similar in composition to lunar basalt. Thickness of these fims was around one micron. There is no broad absorption band due to ferrous iron.

Figure 3. Maxwellian distributions of speed of vapor species at 3000° K. Note mass dependence of position of the curves relative to lunar escape velocity.

Figure 4. Maxwellian distributions of speed of atoms sputtered at an effective temperature of 10,000° K. Note mass dependence of position of the curves relative to lunar escape velocity.

Figure 5. Maxwellian distributions of speed of atoms sputtered at an effective temperature of 50,000° K. Note mass dependence of position of the curves relative to lunar escape velocity.

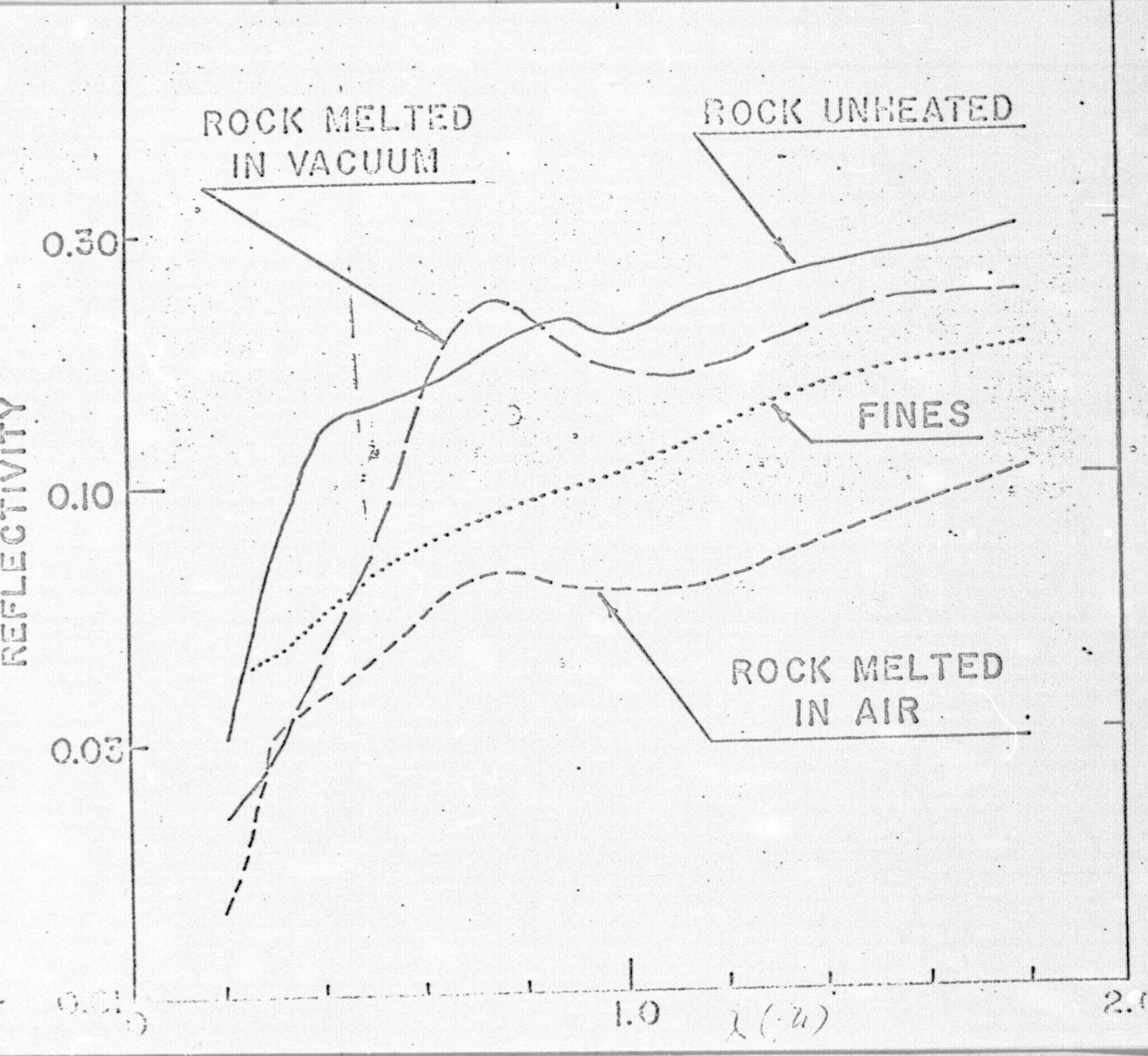
Figure 6. Diagram illustrating crater formation by micrometeorite impact on lunar regolith. If vaporization occurs at close to equilibrium temperatures, vapor fractionation occurs. Vaporized atoms and molecules soon return to surface and form thin amorphous deposits enriched in Si and Fe. Oxygen loss during vaporization produces reduced state upon recondensation.

Figure 7. Diagram illustrating sputter processes. Solar wind protons (inclined, parallel fine lines) strike grain surfaces in lunar regolith. Atoms of high, medium and low atomic weights, represented by heavy, medium, and fine lines, are sputtered from the exposed surfaces. One heavy atom is sputtered upward and may leave the moon. An atom of medium atomic weight is sputtered horizontally, strikes a grain surface, rebounds upward and may leave the moon. Another heavy atom is sputtered horizontally, strikes a grain surface, and sticks. Atoms sputtered in the hole are trapped: their sites are changed, but no net fractionation occurs.

Figure 8. Experimentally obtained sputter fractionation data. Lunar-like glass was exposed to a high-angle flux of accelerated hydrogen atoms. Sputtered material was caught on a molybdenum foil suspended above the sample in such a configuration that sputtered atoms would strike it only once and either stick or rebound from it. A sputter-deposited film 5-10μ thick was built up on the foil; then both film and parent bead were analyzed by electron microprobe. Heavy elements were found to be systematically enriched in the film, indicating that the

heavier the sputtered atom the greater its tendency to stick to the first surface it strikes. Note that this also produces marked oxygen depletion in the film. The experiment was carried out with 2 KeV protons striking the sputtered surface with a current density of 0.33 mA/cm^2. The sputter-deposited film accumulated at an approximate rate of 0.05 microns/hr.

Figure 9. Similar sputtering experiment to that of Figure 8, with identical experimental conditions except the proton beam was directed into a rough-sided rectangular hole in the sample glass. It struck the glass at a low angle and sputtered material was caught on a molybdenum foil inside the hole. This configuration modeled the trapping of sputtered atoms in a hole in the regolith. Very little film/bead fractionation occurred among most elements for which we analyzed, but what fractionation there was followed the mass dependency shown in Figure 8. Exceptions were Na and K, which had been disregarded in the determination of data for Figure 8 because of their extremely low concentrations in the sputter-deposited film.


ROCK MELTED
IN VACUUM
ROCK UNHEATED
FINES
ROCK MELTED
IN AIR
REFLECTIVITY
0.30
0.10
0.03
0.01
1.0
2.0
λ (μ)

Figure

Figure

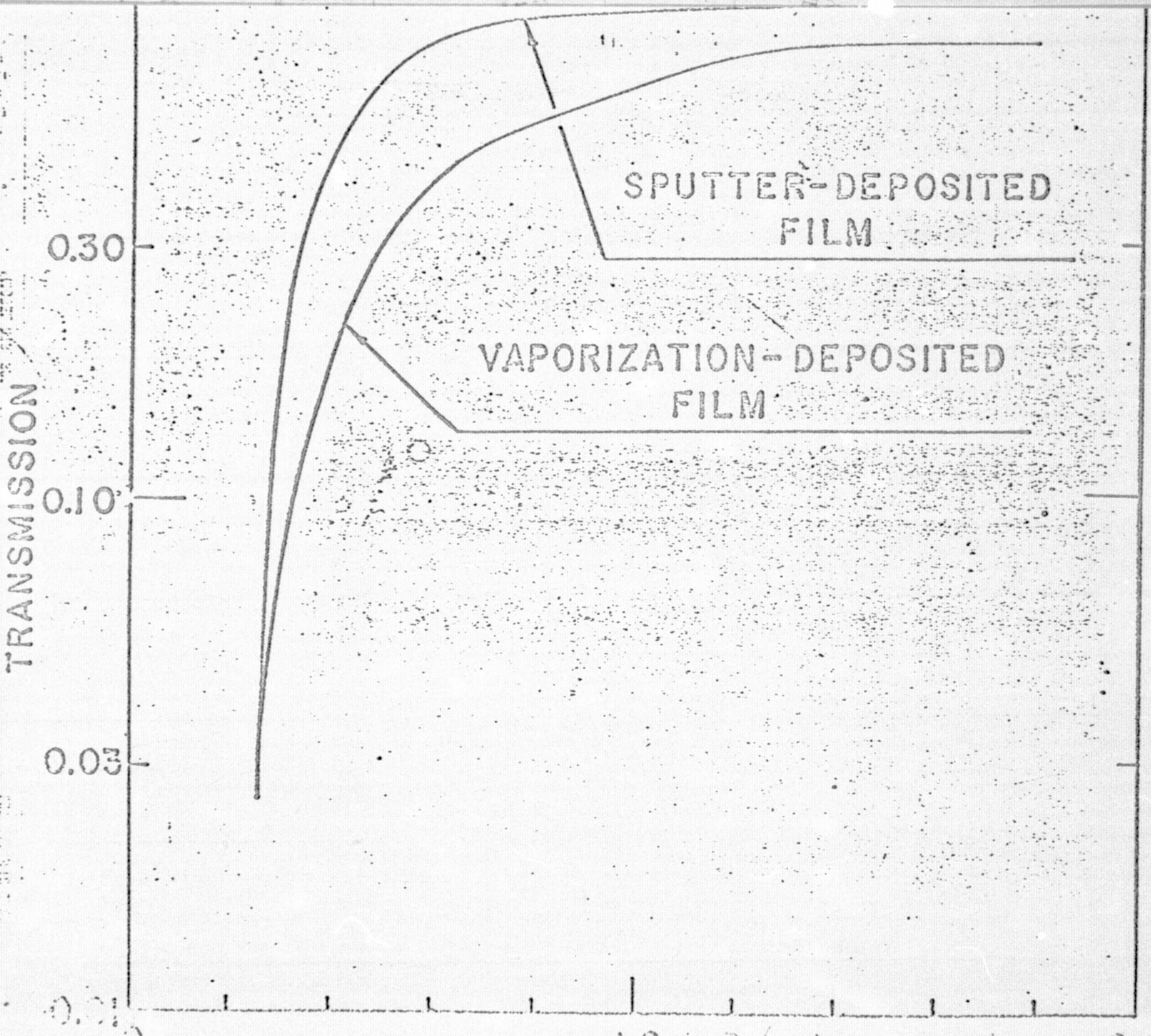

TRANSMISSION
0.30
0.10
0.03
0.01
SPUTTER-DEPOSITED FILM
VAPORIZATION-DEPOSITED FILM

Figure 3

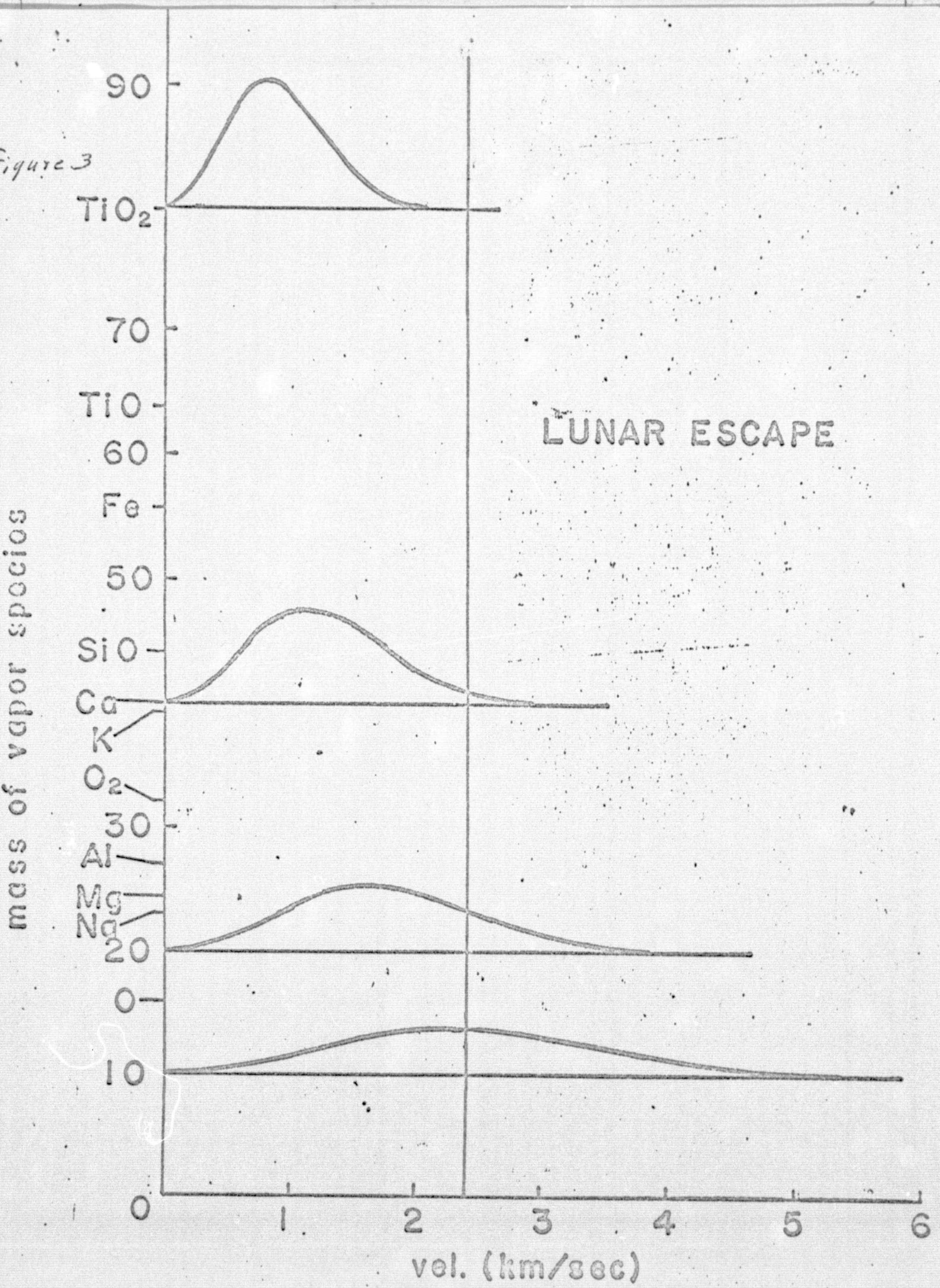
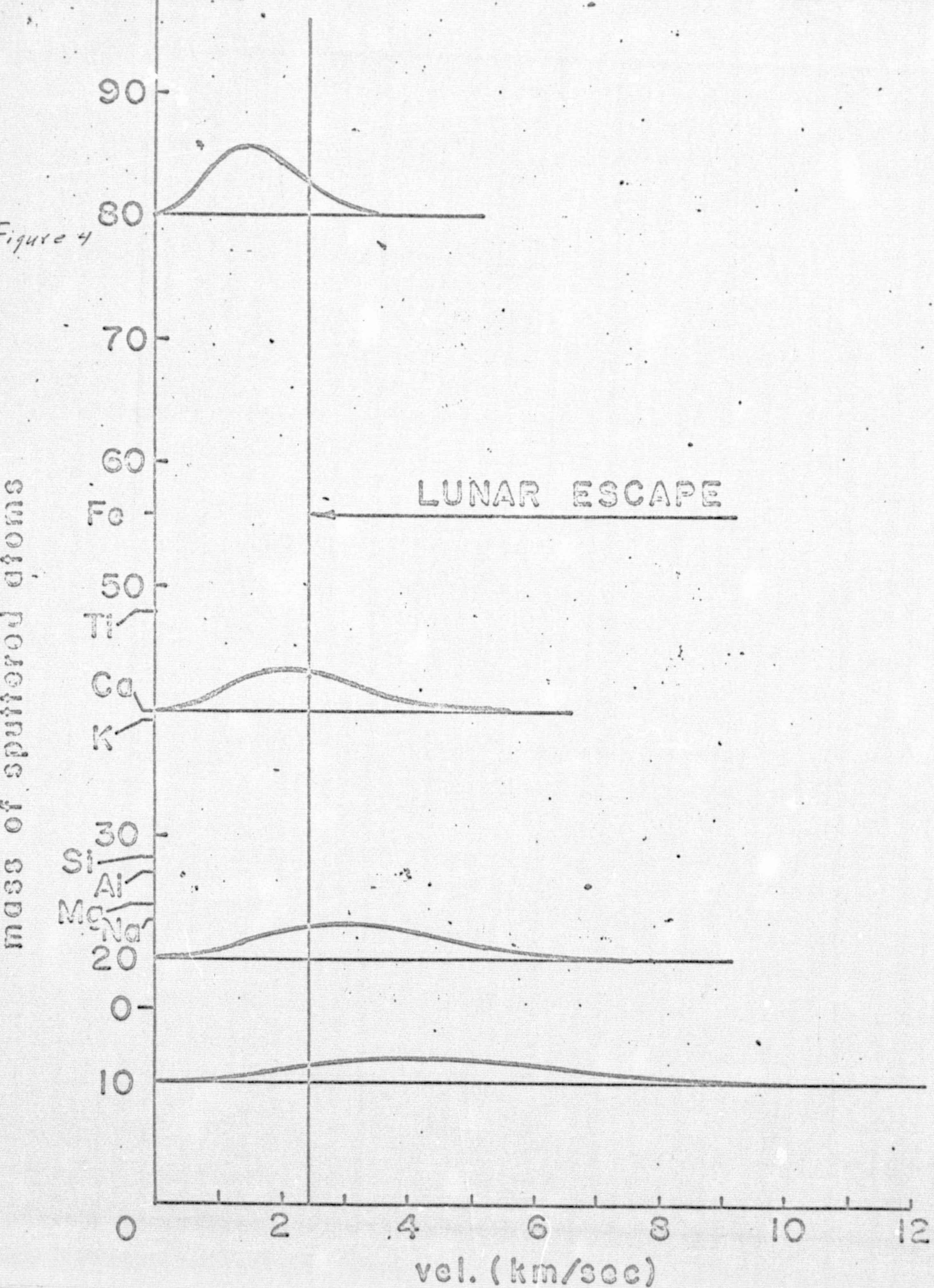
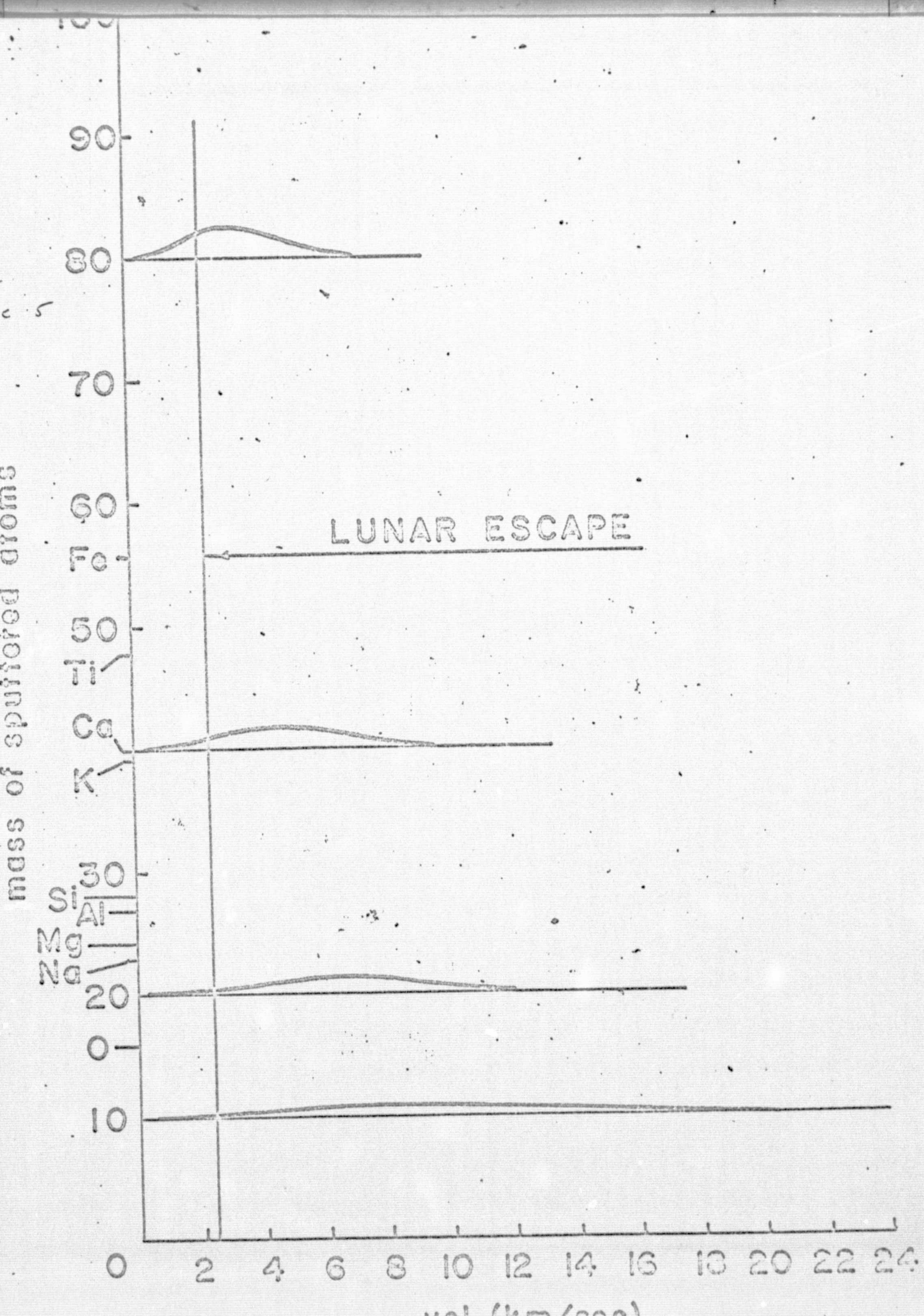

LUNAR ESCAPE
mass of vapor species
vel. (km/sec)
90
TiO2
70
TiO
60
Fe
50
SiO
Ca
K
O2
30
Al
Mg
Na
20
O
10
0
1
2
3
4
5
6

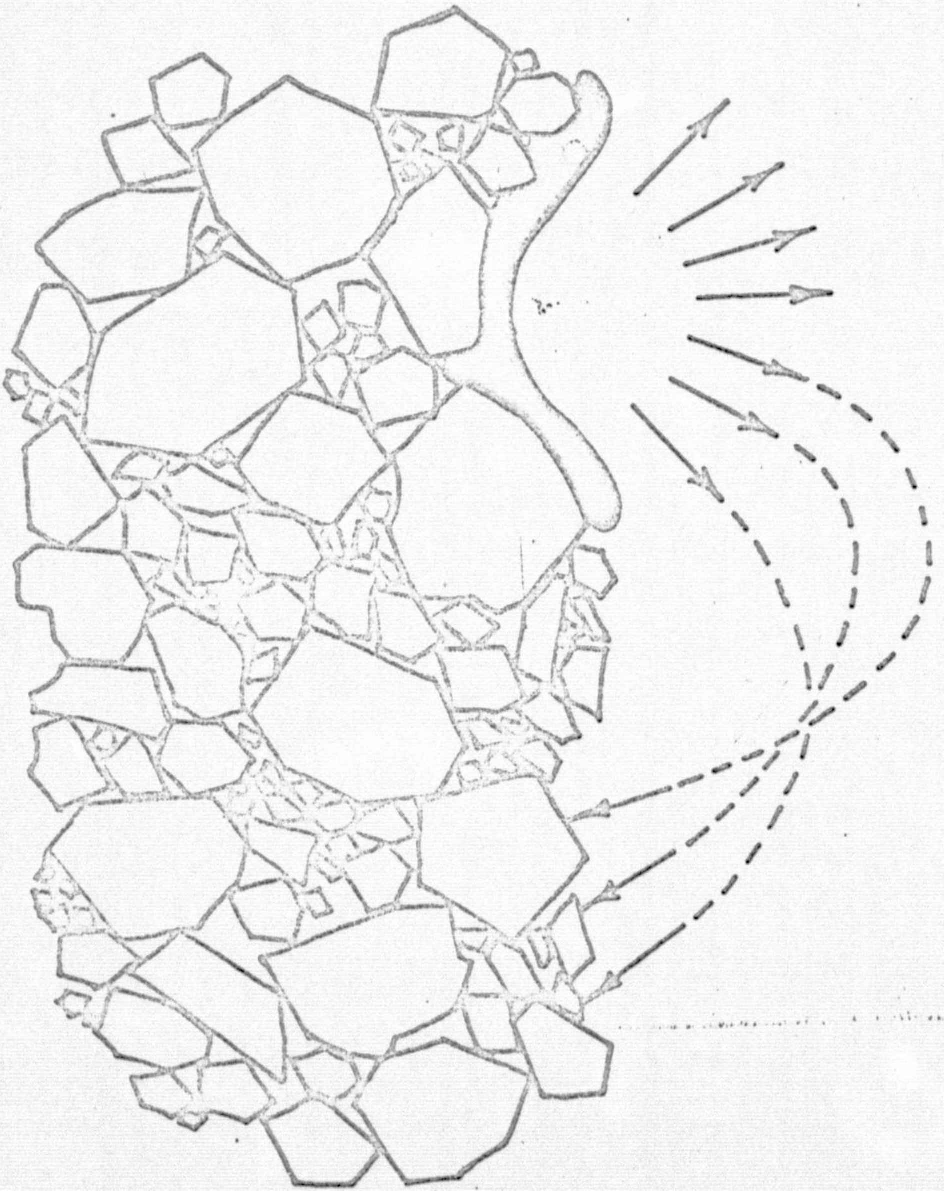
Figure 4



90
80
70
60
Fe
50
Ti
Ca
K
30
Si
Al
Mg
Na
20
0
10
LUNAR ESCAPE
mass of sputtered atoms
0
2
4
6
8
10
12
vel. (km/sec)

igure 5


mass of sputtered atoms
90
80
70
60
Fe
50
Ti
Ca
K
30
Si
Al
Mg
Na
20
O
10
LUNAR ESCAPE
0
2
4
6
8
10
12
14
16
18
20
22
24
vel (km/sec)



Fig

Figure 7

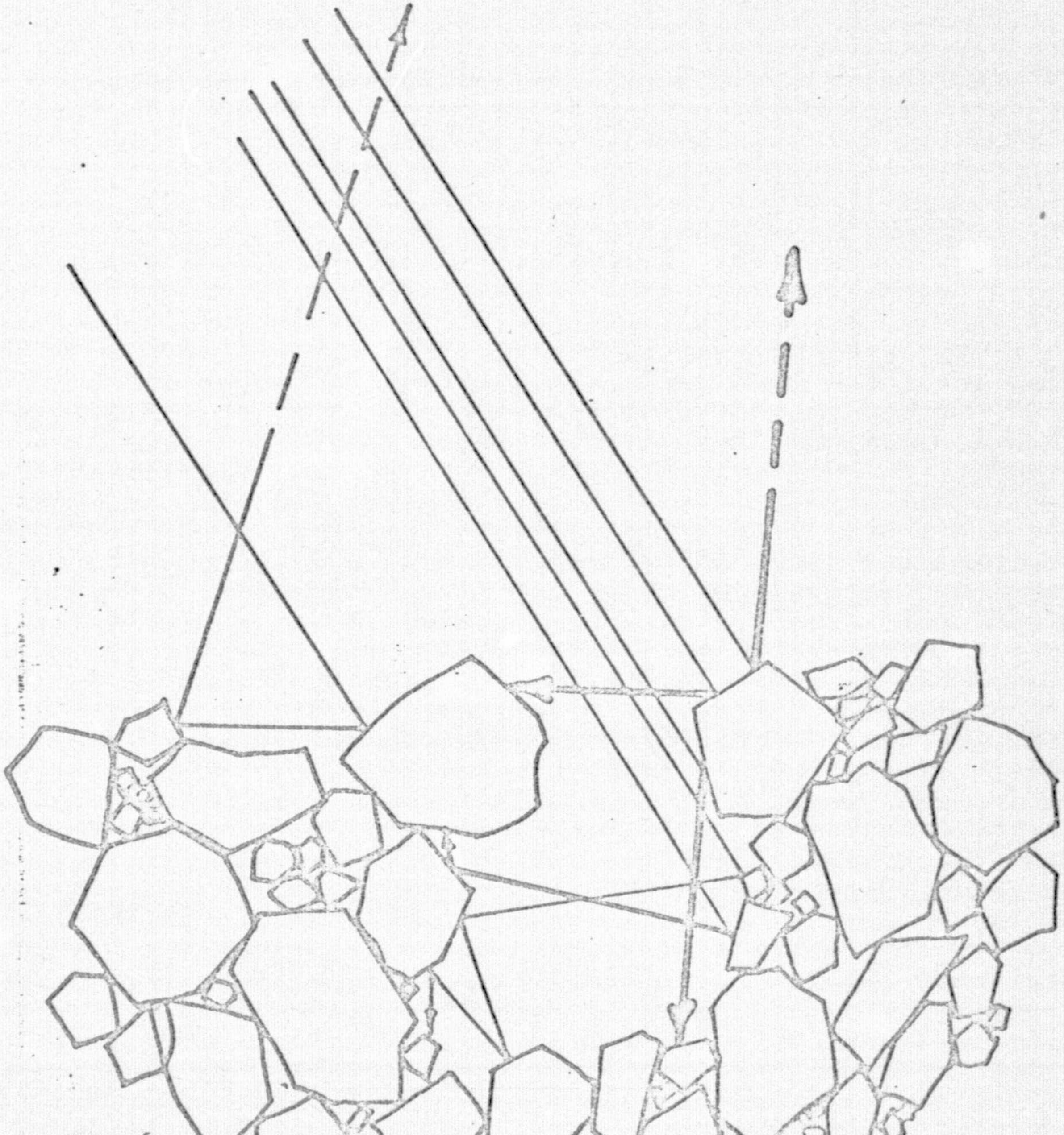


Figure 8

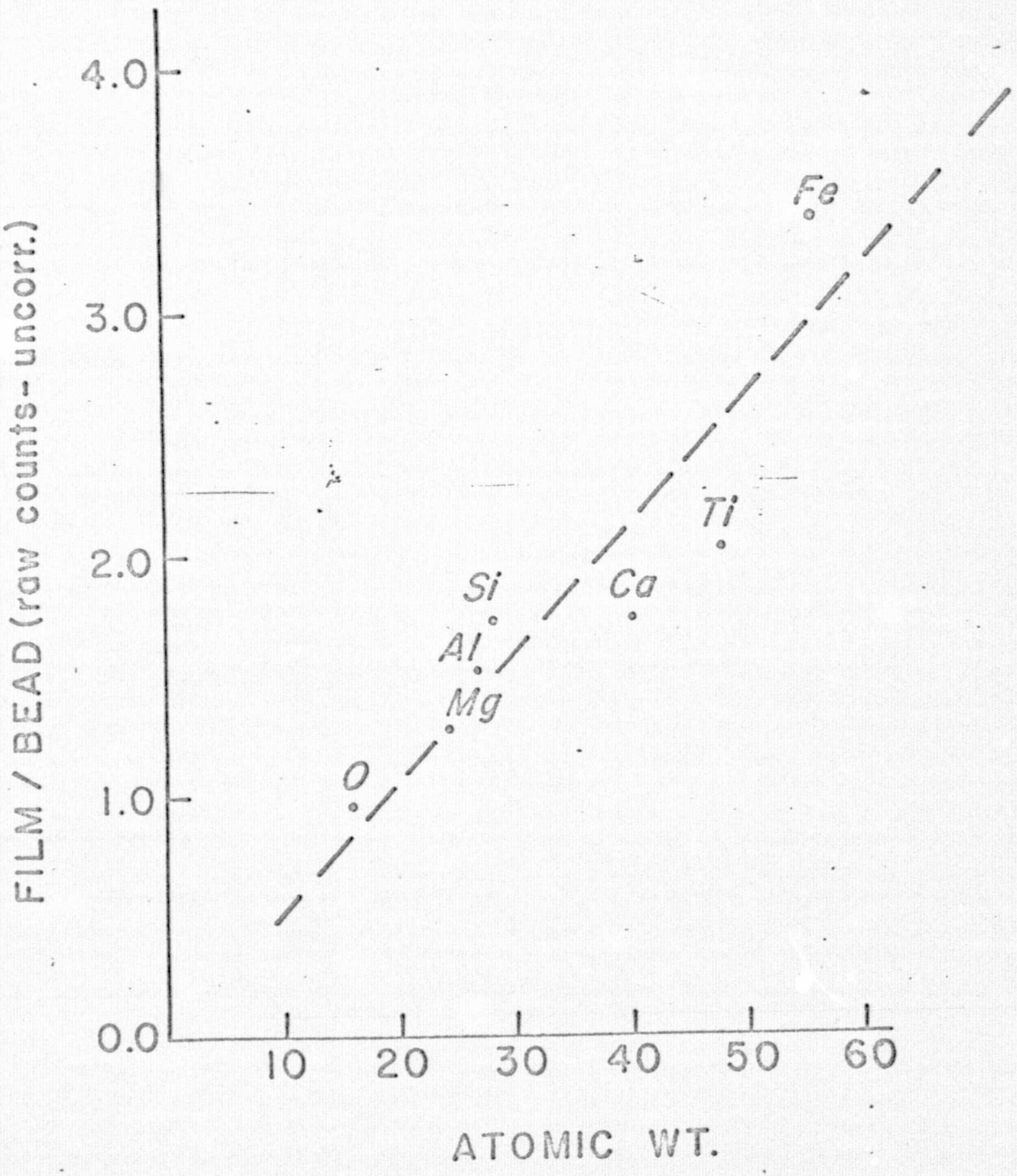
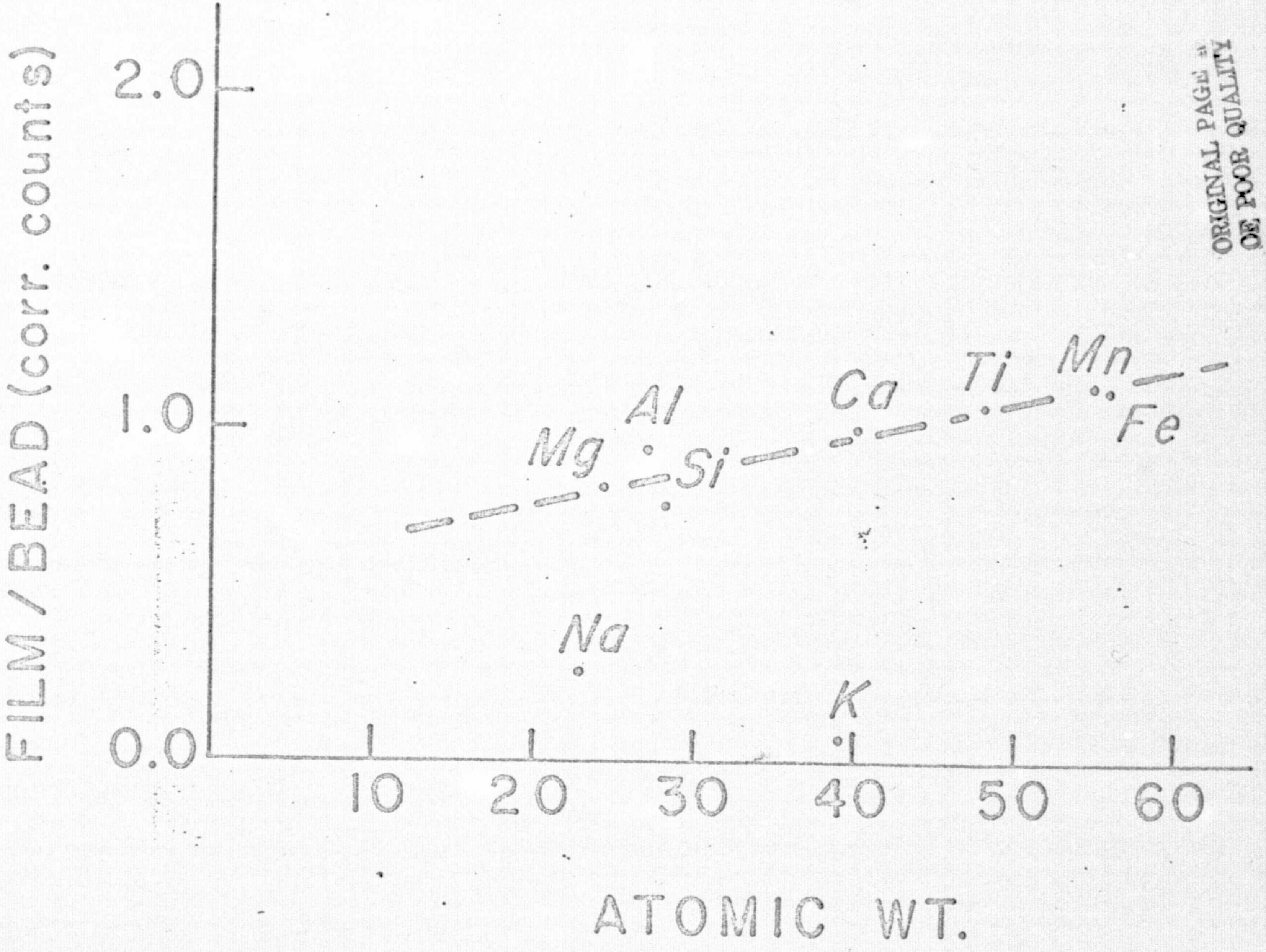

FILM / BEAD (raw counts- uncorr.)
4.0
3.0
2.0
1.0
0.0
10
20
30
40
50
60
ATOMIC WT.
Fe
Ti
Ca
Si
Al
Mg
O

Figure 9


FILM / BEAD (corr. counts)
2.0
1.0
0.0
10
20
30
40
50
60
ATOMIC WT.
Mg
Al
Si
Ca
Ti
Mn
Fe
Na
K