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USE OF RADIATION GAUGING METHODS TO MEASURE ATMOSPHERIC DENSITY DURING MARTIAN ENTRY

J. W. Ranftl

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PREFACE

This Memorandum evaluates radiation gauging as a method for measuring the density profile of the Martian atmosphere, using an unmanned probe. Underlying the evaluation is a delineation of the parameters of the Martian atmosphere. From this, design limits for experiments and instrumentation are established. The report also suggests areas of development to assist those concerned with radiation instrumentation suitable for obtaining data necessary for a manned landing vehicle.

This Memorandum is one of two that support a more general study of measurement of the Martian environment, RM-4437-NASA, Mars Environmental Measurements in Support of Future Manned Landing Expeditions, by W. H. Krase, April 1965. The other is RM-4451-NASA, Instrumentation To Measure Mars' Atmospheric Composition, Using a Soft-landed Probe, by R. A. Woods and J. W. Ranftl, April 1965.

All three Memoranda contribute to the Apollo Contingency Planning Study undertaken by The RAND Corporation for Headquarters, National Aeronautics and Space Administration, under Contract NASr-21(09).

The author of the present Memorandum is a consultant to the System Operations Department of The RAND Corporation.

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SUMMARY

This study evaluates radiation gauging methods for use in an unmanned probe to measure the density of the Martian atmosphere during entry. The problem is one of making accurate measurements, most likely under high speed flight conditions, in an environment about which little is known, and with limited responsive communications to earth because of the great distance involved. Because of these stipulations, instrumentation for the Martian flight must be extremely reliable and capable of functioning over a wide range of environmental and ambient conditions.

Certain conclusions have been made on the basis of this study:

1. Except for the remoteness of the location and unknown factors in composition, the Martian atmosphere presents a gauging problem quite similar to that of gauging the density of the terrestrial atmosphere from a rapidly moving vehicle.

2. Of the several techniques available, X-ray backscattering with an electrically generated, continuously operating source of radiation appears to be the most promising method for gauging atmospheric density in the range of 10^{-8} to 10^{-3} gm/cm^3. This range extends from those densities that are significant in entry effects (the lesser value) to the estimated near-surface density of Mars (the greater value). The use of an electron beam, generating soft X-rays (bremsstrahlung), is suggested as an auxiliary technique for gauging in the range of 10^{-12} to 10^{-8} gm/cm^3, with a possible extension to 10^{-7} gm/cm^3 to overlap the X-ray range.

Author

3. Certain estimates can be made for the instrumentation package:

weight	15 to 20 lb
volume	400 cubic inches
power	100 watts
data rate	20 bits per determination; one determination per second

Incorporating the electron beam source to function in the range of 10^{-12} to 10^{-8} gm/cm^3 would add to the package approximately 2 to 5 lb in weight, 100 cubic inches in volume, and 10 watts in power.

4. Gauging accuracy will be influenced by the selection of the flight mode because of the effect that vertical velocity has on the change of density during the sampling and measurement period. The details of instrument design will also affect the accuracy because of the influence on the strength of the response signal. Tentatively, accuracies on the order of 5 to 20 per cent, depending on the density range, appear feasible.

5. Continued work on terrestrial atmospheric density gauging should contribute significantly to the Martian effort. It is important, however, that additional programs directly oriented to the Mars mission be initiated. This Memorandum suggests areas for future research and development. These include the further study of pulsed techniques and the investigation of X-ray emission spectroscopy for a possible simultaneous determination of density and composition.

ACKNOWLEDGMENTS

The author wishes to thank those people at RAND who gave suggestions and comments on this study and, in particular, Gerhard Schilling for his most helpful discussion of the parameters of the Martian atmosphere.

Further appreciation is extended to the industrial firms that made information available on related instrumentation and to the people in the National Aeronautics and Space Administration and the U.S. Air Force for test results of terrestrial atmospheric density gauging.

CONTENTS

I. INTRODUCTION

An important prerequisite for spacecraft design and reentry planning for terrestrial flights is an accurate knowledge of atmospheric density. A similar knowledge of the Martian atmosphere is necessary for effective Mars flight regimes, whether these flights will include actual landing, low-level orbiting, or fly-by in the atmosphere. However, determination of the Martian atmospheric density through early probes necessitates making accurate measurements under conditions of high-speed flight in an environment about which little is known. Certain estimates of surface pressure and atmospheric temperature and density profiles have been made for Mars, but the values vary too greatly for accurate flight planning.*

The problem of density measurement is further complicated by the fact that the great distance to Mars limits responsive communication to earth in making such determinations. Because of the conditions imposed, instrumentation for the Martian flight must be extremely reliable over a long period of time and be able to function over a wide range of environmental and ambient conditions. Since the range of probable values is large, the measurement range of the equipment must also be extensive.

Radiation gauging is one method of atmospheric density measurement that meets these requirements and can be used for early unmanned probes, either hard or soft landing. It is based on the principle that the

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*The surface pressure of 85 mb (Ref. 1) that was formerly accepted as accurate is now held to be too high. Schilling (Ref. 2) proposed a range of possible values, indicating that a considerably lower surface pressure might be found. Subsequently, on the basis of a new measurement, Kaplan et al. (Ref. 3) have calculated a surface pressure of 25 ± 15 mb.

atmosphere will cause scattering and absorption of radiation; the more dense the atmosphere, the greater will be the effect. The aerodynamic application of radiation gauging was first investigated in 1944 at Peenemunde.(4) This early work utilized transmission attenuation and relied upon film as the X-ray detector. Such a method of detection, however, limits the speed, accuracy, and resolution of the determinations. Further progress was made in a later application, reported in 1952 by Dimeff et al.,(5) that incorporated electronic measurement of X-ray beam intensities. This work involved the instrumentation of a 10 by 14 in. wind tunnel and was significant for its use of very small beams of low energy X-rays. Beams a few thousandths of an inch in diameter gave a high resolution in the determination of density gradients normal to the beam direction. Recent investigations, more directly related to use in Martian probes, have utilized radiation scattering measurements that do not require in-line geometry and are accordingly better suited for operation in rapidly moving vehicles.

Based on a survey of other possible density gauging methods, radiation gauging appears to be outstanding for application during high-speed entry into planetary atmospheres.* It can be made to function in the presence of shock layer effects, gauging ambient densities relatively independently of density increases caused by the vehicle. Additionally, the density determination is not affected by either vertical or horizontal air movement. Other methods of measuring density by direct sampling do not seem as feasible as the radiation method

*Reference 6 discusses some other possible methods.

because of the uncertain but high variations of density around the vehicle and because of possible spurious effects that could result from ablation and heat transfer.

A method of deducing density from vehicle drag measurements has also been proposed and has received considerable attention. A full discussion of this method is not within the scope of this study, which notes only that such drag deductions have the following limitations: (1) they are not likely to be accurate at either high or low altitudes where the deceleration is small, (2) they are, for most probable body shapes, dependent upon the attitude of the vehicle, and (3) they require a substantial amount of auxiliary data for their interpretation. However, because the drag method does not require much additional instrumentation and since this method permits redundancy of measurement in a certain altitude range, density deductions based on deceleration measurements can be used in a Mars probe in addition to the radiation methods discussed in this study.

This Memorandum will present an analysis of how the radiation gauging method can be applied in relation to the variables in the Martian atmosphere. This study will also define suitable techniques and suggest future areas of development.

II. THE MARTIAN ATMOSPHERE

In order to consider the application of radiation density gauging, it is necessary to establish ranges of the values that are likely to be encountered. The density values are of interest in considering the strength of response signals. The rate of change of density is important in establishing sampling periods, particularly in the case of high-speed flight. Composition ranges are important because of their possible effect on scattering response.

DENSITY RANGE

The density range greater than 10^{-8} gm/cm^3 is of greatest interest, since it is in that range that reentry heating and aerodynamic effects become marked. However, in order to get as complete a profile as possible of the Martian atmosphere, it is desirable to consider measuring densities as low as 10^{-12} gm/cm^3.

In Fig. 1, various models of the Martian atmosphere have been plotted. The models are named according to the value for surface pressure, e. g., the 20 mb model corresponds to a surface pressure of 20 millibars. The earth's atmosphere is included as a reference line. Numerical values and their derivations are given in Appendix A. All models indicate a surface pressure considerably lower than that of the earth, but with lesser rates of change as a function of altitude. It is expected that the Martian atmosphere will equal and exceed the density of the earth's atmosphere at corresponding higher altitudes. However, the overall range of values to be considered is quite similar to that encountered in measuring terrestrial values,

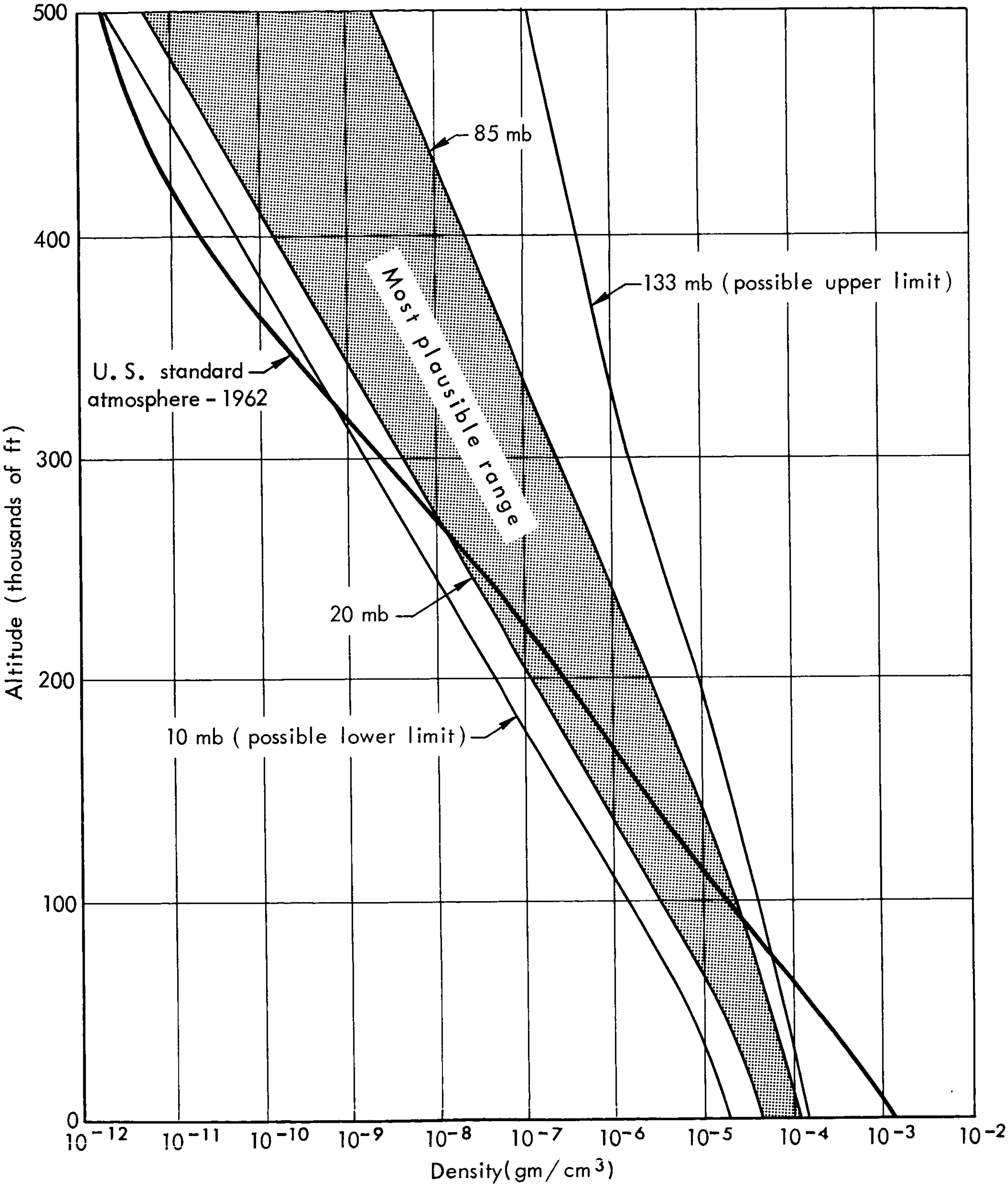

Fig. 1—Martian atmospheric models compared to Earth's atmosphere

and consequently information gained from flights in the earth's atmosphere should provide a valid basis for designing Martian probe instrumentation.

RATE OF CHANGE OF DENSITY WITH ALTITUDE

For the purpose of establishing rate of change to the degree of accuracy required for the present analysis, density can be expressed as a function of altitude by the relation

$$\rho_Z = \rho_o \exp^{-Z/H} \tag{1}$$

in which

ρ_Z = density at altitude Z (gm/cm^3)

ρ_o = density at the surface (gm/cm^3)

H = scale height (thousands of ft)

Z = geometric altitude (thousands of ft)

The ratio of densities at two different altitudes can be expressed as

$$\frac{\rho_1}{\rho_2} = \frac{\rho_o \exp^{-Z_1/H}}{\rho_o \exp^{-Z_2/H}}$$

or

$$\frac{\rho_1}{\rho_2} = \exp^{-\left(\frac{Z_1 - Z_2}{H}\right)} \tag{2}$$

For a more detailed discussion of atmospheric parameters the reader is referred to earlier reports by Schilling.[2, 7]

Examining Fig. 1, note that the density approximately follows such exponential relationships in the range of 100,000 to 500,000 ft for the 10, 20, and 85 mb models. At lower altitudes also (0 to 60,000 ft and 60,000 to 100,000 ft) the change can be approximated as exponential functions between the corresponding points. The upper limit, 133 mb model can be considered as a single exponential function in the full range. These approximations are adequate for the present purpose of establishing ranges of rate of change of density as a function of altitude.

By use of data in Appendix A, the following values have been calculated.

Table 1

MARTIAN ATMOSPHERIC DENSITY CONSTANTS

Atmosphere	Altitude Range (thousands of ft)	ρ_o (gm/cm^3)	H Scale Height (thousands of ft)
10 mb	100-500	4.78×10^{-5}	29.5
	60-100	4.19×10^{-5}	31.3
	0-60	1.82×10^{-5}	55.6
20 mb	100-500	9.56×10^{-5}	29.5
	60-100	8.37×10^{-5}	31.3
	0-60	3.63×10^{-5}	55.6
85 mb	100-500	2.39×10^{-4}	42.7
	60-100	1.52×10^{-4}	55.6
	0-60	1.19×10^{-4}	71.4
133 mb	0-500	1.49×10^{-4}	68.0

The limits of percentage change in density encountered by a descending probe as a function of distance traveled is easily determined by the use of equation (2) and the constants contained in the above table.

In descending from altitude Z_1 to altitude Z_2, the density increases from ρ_1 to ρ_2. The percentage increase can be expressed as

$$P = 100\left(\frac{\rho_2 - \rho_1}{\rho_1}\right) = 100\left(\frac{\rho_2}{\rho_1} - 1\right)$$

Substituting from equation (2)

$$P = 100\ (\exp^{\Delta Z/H} - 1) \tag{3}$$

The percentage change has been calculated for the various models of the Martian atmosphere and is summarized in Fig. 2. It is evident that the low pressure or lower limit models produce the greatest change in density as a function of altitude. Thus density gauging apparatus should be designed for the higher change rate.

Figure 3 illustrates the possible variations for a given vertical distance traveled. As an example, in a descent of 5000 ft, the atmosphere might increase 18 per cent in density for the lower limit model and at least 7 per cent for the upper limit model.

Another application of the density change data is illustrated in Fig. 4. If the measurement is to be made during a time when the change is not greater than 25 per cent, the vertical distance traveled could range from 7000 to 15,000 ft. At a vertical velocity of 10,000 ft/sec, the measurement period would be in the range of 0.7 to 1.5 sec.

RELATION OF DENSITY CHANGE TO ENTRY MODE

The density changes have all been calculated on a basis of vertical distance traveled, which corresponds to vehicle travel only

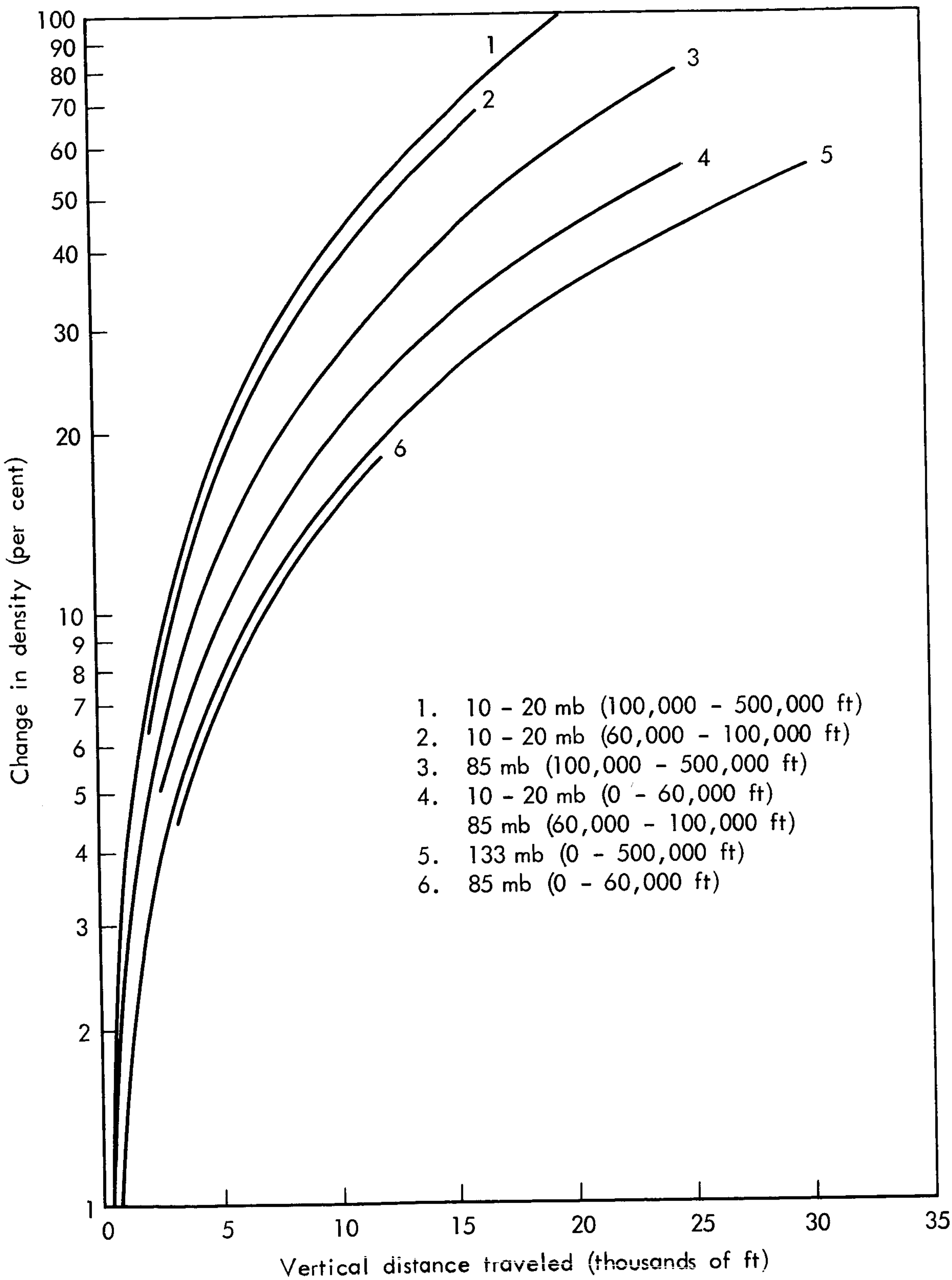

Fig. 2—Percentage of change in density for vertical distance traveled

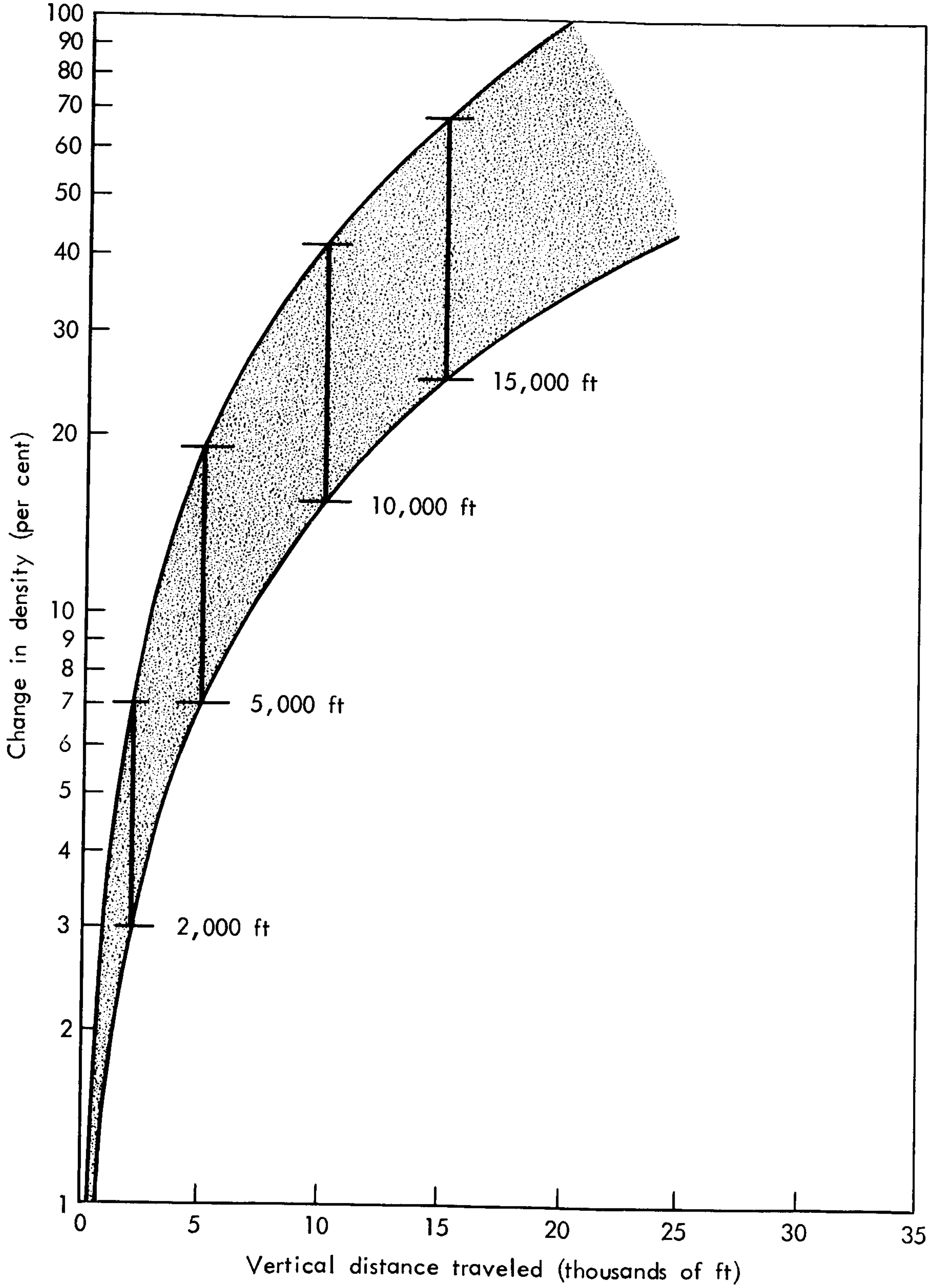

Fig. 3—Range of density change for a specified vertical distance

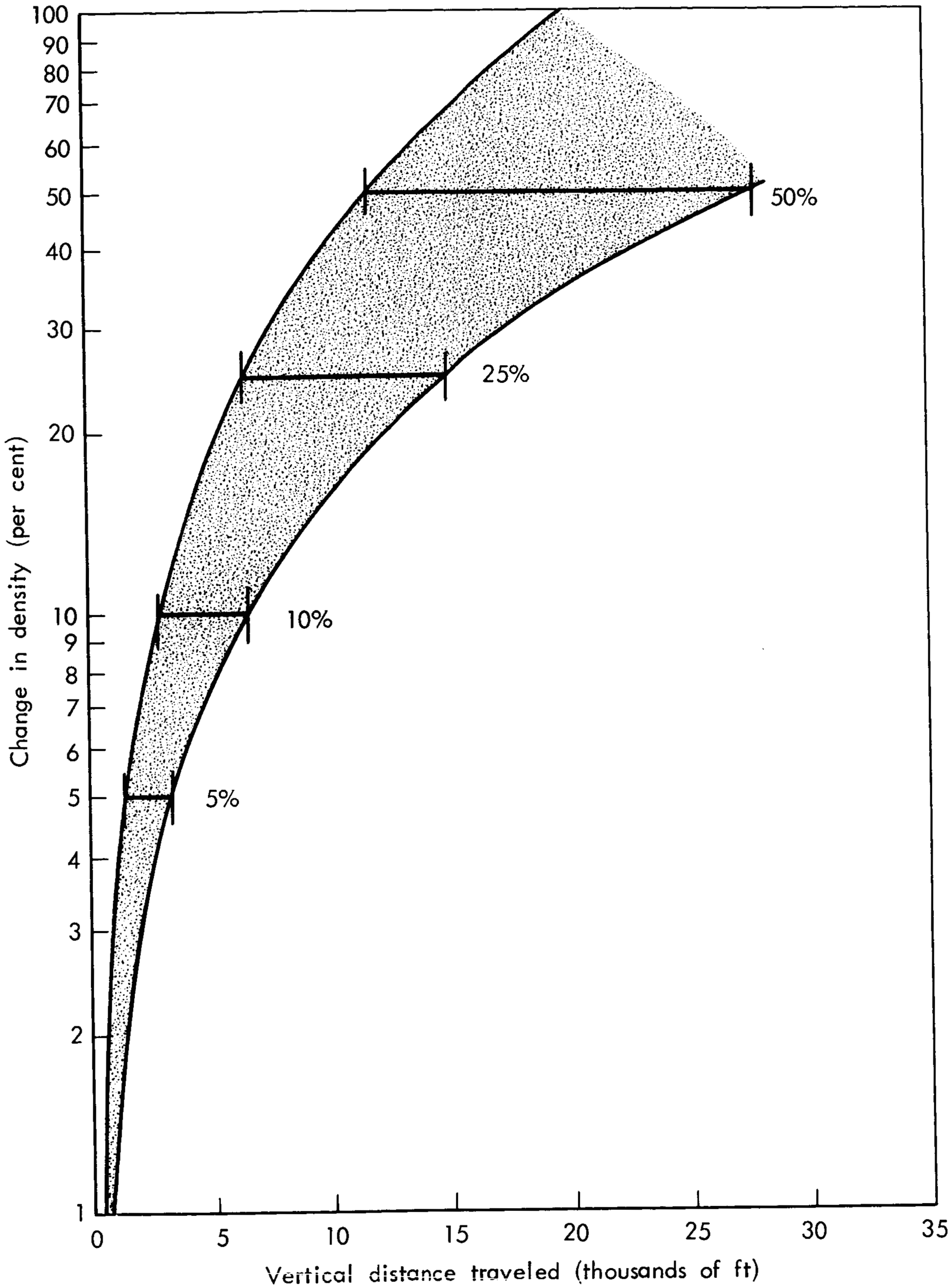

Fig. 4—Range of allowable vertical distance traveled for a specified change in density

for vertical descent or a 90-deg angle. Entry at other angles will result in less vertical travel for given vehicle travel; e.g., at a 30-deg entry angle, the vertical velocity component is one-half of the vehicle velocity. Density changes will be calculated from vertical velocity components multiplied by the time of travel during the sampling period.

COMPOSITIONAL VARIATION

It has not been possible to accurately determine the composition of the Martian atmosphere from earth-based measurements. The presence of carbon dioxide has been detected and nitrogen and argon have been proposed as other constituents. The different ranges of composition that have been proposed vary widely, as illustrated in Table 2. These three atmospheres were selected to include maximum values for CO_2, A, and N_2, respectively.

Table 2

VOLUMETRIC COMPOSITION OF MARTIAN ATMOSPHERE

	Kaplan 10 mb	Kaplan 25 mb	de Vaucouleurs 85 mb
CO_2	60%	16%	0.3%
N_2	20%	8%	98.5%
A	20%	76%	1.2%

Since composition can have an effect on density determination by the radiation method, molecular weight and weight fractions were calculated for several Martian atmospheres and are tabulated in

Appendix B. The models with the lowest surface pressure generally have the greatest molecular weight. For any composition it is expected that the molecular weight at high altitudes will be less than at the surface because of dissociation of the gases present. Additionally, and especially pertinent to high argon atmospheres, it is expected that gravitational separation effects will tend to hold the heavier constituents in greater proportional concentration at lower altitudes. Because of the many uncertainties about the Martian atmosphere, it is not practical to consider in greater detail the change in composition and molecular weight as a function of altitude.

III. THE DENSITY GAUGING PROCESS

ABSORPTION AND SCATTERING

In passing through matter, radiation is attenuated by interaction with the substances present. The degree of attenuation will vary with the energy or wavelength of the radiation and the substances present. Also, the exact nature of the reactions causing attenuation will vary with the type and energy of the radiation. Some typical reactions are:

(1) Coherent scattering in which the direction of radiation is changed, but the energy level remains the same

(2) Incoherent or modified scattering in which both direction and energy are changed

(3) Absorption processes causing photoelectron emission and the emission of radiation characteristic of the absorbing material.

The radiation gauging principle involves measuring the degree of attenuation by these processes to determine the amount of material contributing to the effect. In the case of a gas for which a constant volume is used for measurement, the attenuation will be a function of the density of the gas. In considering the instrumentation method, it is possible to measure the intensity of the emergent radiation beam as an inverse function of density. Alternatively, the intensity of the scattered radiation will increase with increasing density. Figure 5 illustrates this process. Scattering will take place in all directions, some of which will be in the direction of the primary beam of radiation.

AVAILABLE RADIATIONS

Using radiation for density gauging offers a wide selection of techniques, not only in the geometry of application, but also in the

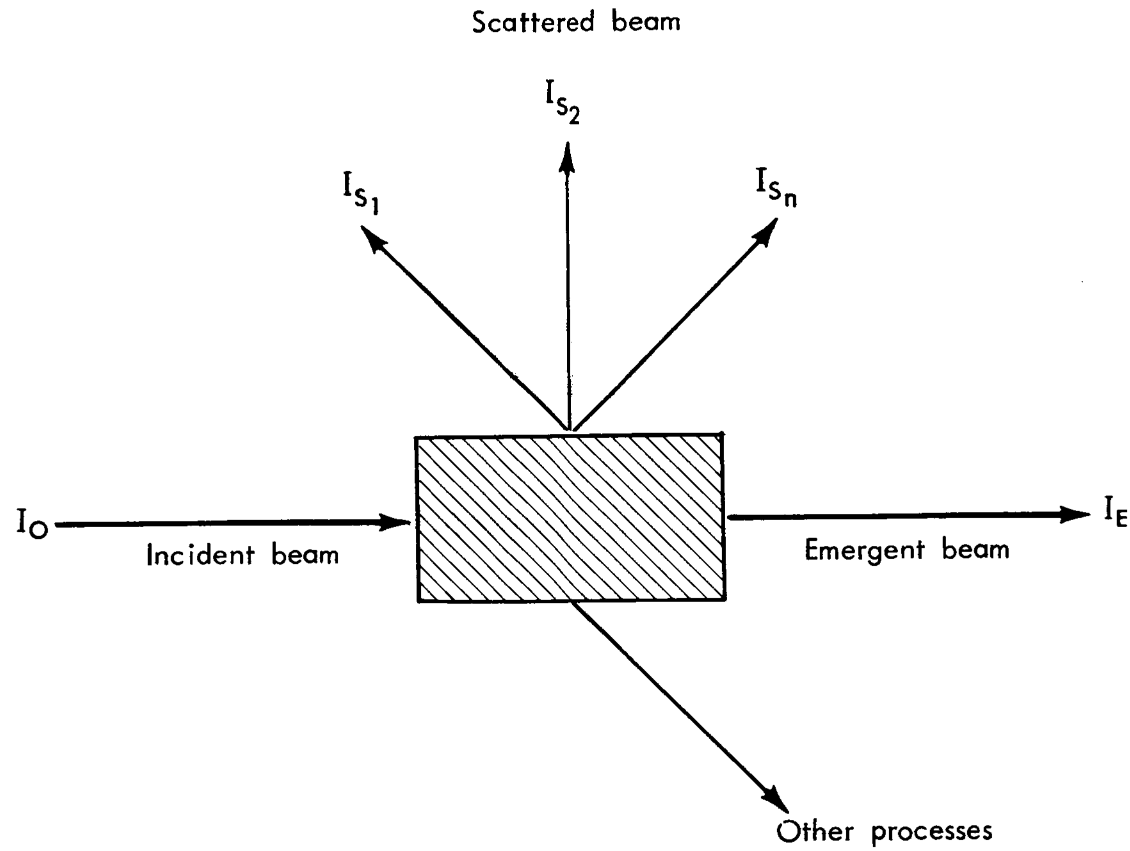

Fig.5—Absorption and scattering

choice of the source of radiation. Many different methods might be used, but some will be very limited in their application.* The radiations considered in this study include:

1. Gamma Rays - highly penetrating electromagnetic radiation resulting from the decay of certain radioactive materials

2. X-rays - penetrating electromagnetic radiation with properties similar to gamma rays, but machine-generated by the interaction of an electron beam with a target material (normally a high atomic number metal)

3. Beta Rays - fast electrons resulting from radioactive decay processes (of low penetrating power)

4. Electron Beams - machine-generated and accelerated electrons (of very low penetrating power)

5. Alpha Radiation - positively charged particle radiation corresponding to helium nuclei, resulting from radioactive decay processes (of extremely low penetrating power)

The penetration of radiation varies widely with type and energy as illustrated by a few typical values contained in Table 3.

Table 3

PENETRATION OF TYPICAL RADIATIONS IN AIR

Radiation	Range in Air (1.225×10^{-3} gm/cm^3)
2 MEV alphas	1 cm
5 MEV alphas	4 cm
0.1 MEV electrons	22 cm
1 MEV electron	300 cm
0.1 MEV X-ray	3700 cm[a]

[a] The value given is the distance calculated for which the intensity would be reduced to one-half the original intensity by virtue of the absorption and scattering process. The actual intensity at such a distance would be less because of the divergence of the radiation.

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*As an example, ultra-violet radiation (near-visible) offers possibilities as a radiation source but is limited in application because of density range considerations, sensitivity to the composition of the scattering medium, and likely interference effects from the solar background.

This table illustrates the extreme penetration of gamma rays and X-rays--radiation of only a few thousand volts of energy is very penetrating in terms of upper atmospheric densities. More complete information on penetration is available in many texts, such as Segré.(7)

GAUGING GEOMETRY

Figure 6 illustrates the simple geometry of various types of gauging. Applying these techniques to space probes, it is apparent that transmission gauging would require (1) gauge elements external to the spacecraft or (2) the introduction of an atmospheric sample into the volume of the spacecraft if the gauging system were internal to the craft. Further, the transmission system would give an average value of density over the entire length of sample corresponding to the distance between the source and the detector and would likely not be representative of ambient conditions because of shock layers and other possible extraneous effects.

Low-angle scatter has some of the same geometrical limitations found in the in-line transmission system. An in-board system would have a path almost entirely in the shock layer area for any reasonable source-detector separation distance and would not give readings representative of ambient conditions.

Back-scatter offers the widest selection of practical instrumentation for use on a space probe. The effect of the shock layer is minimized, since the scattering volume is outside that region and only differences due to absorption in the denser shock layer must be accounted for. These are small for radiation of high penetration.

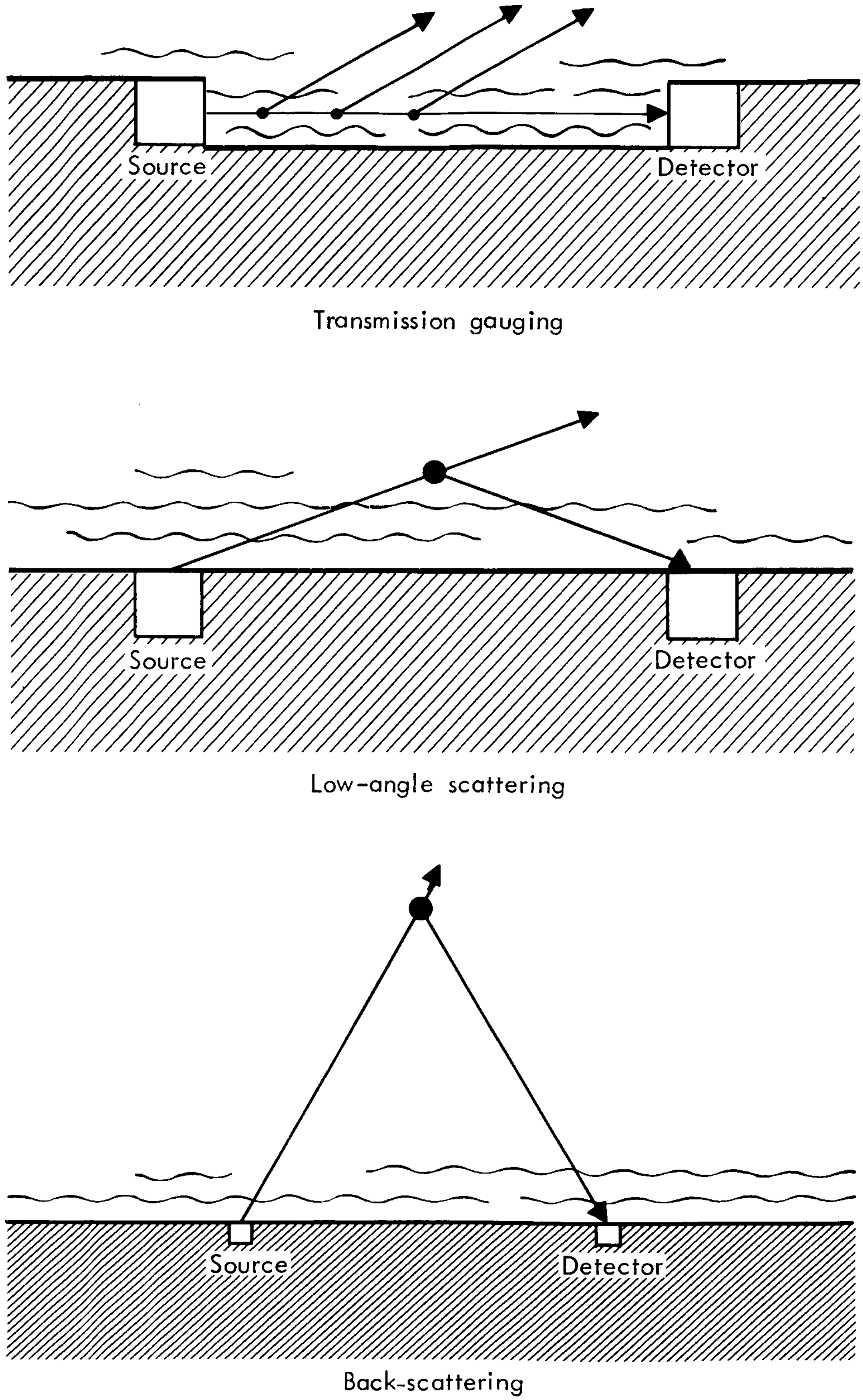

Fig. 6—Gauging geometries

Figure 7 illustrates the back-scatter gauging principle in greater detail. The source is collimated to exit as a divergent beam of radiation. The atmosphere will cause scattering along the entire length of the beam. In order to restrict and better define the active scattering volume, the radiation detector is also collimated. The amount of scattered radiation received by the detector will be a function of the density of that portion of the atmosphere included in the active volume, shown as the shaded area. The actual volume is three dimensional and is also defined in the other dimension by limits of the beam and detector collimation.

These statements hold because only a small fraction of the beam is scattered or absorbed in path lengths of practical interest (Appendix C), so multiple scattering can be neglected. For the same reason the shock layer of greater density will make no material contribution to the intensity of scattered radiation.

A special case of the back-scatter technique (electron-bremsstrahlung) is the use of an electron source that will generate X-rays in the active sample volume in addition to electron scattering. The detection of the generated X-rays is used as a measure of gas density.[9]

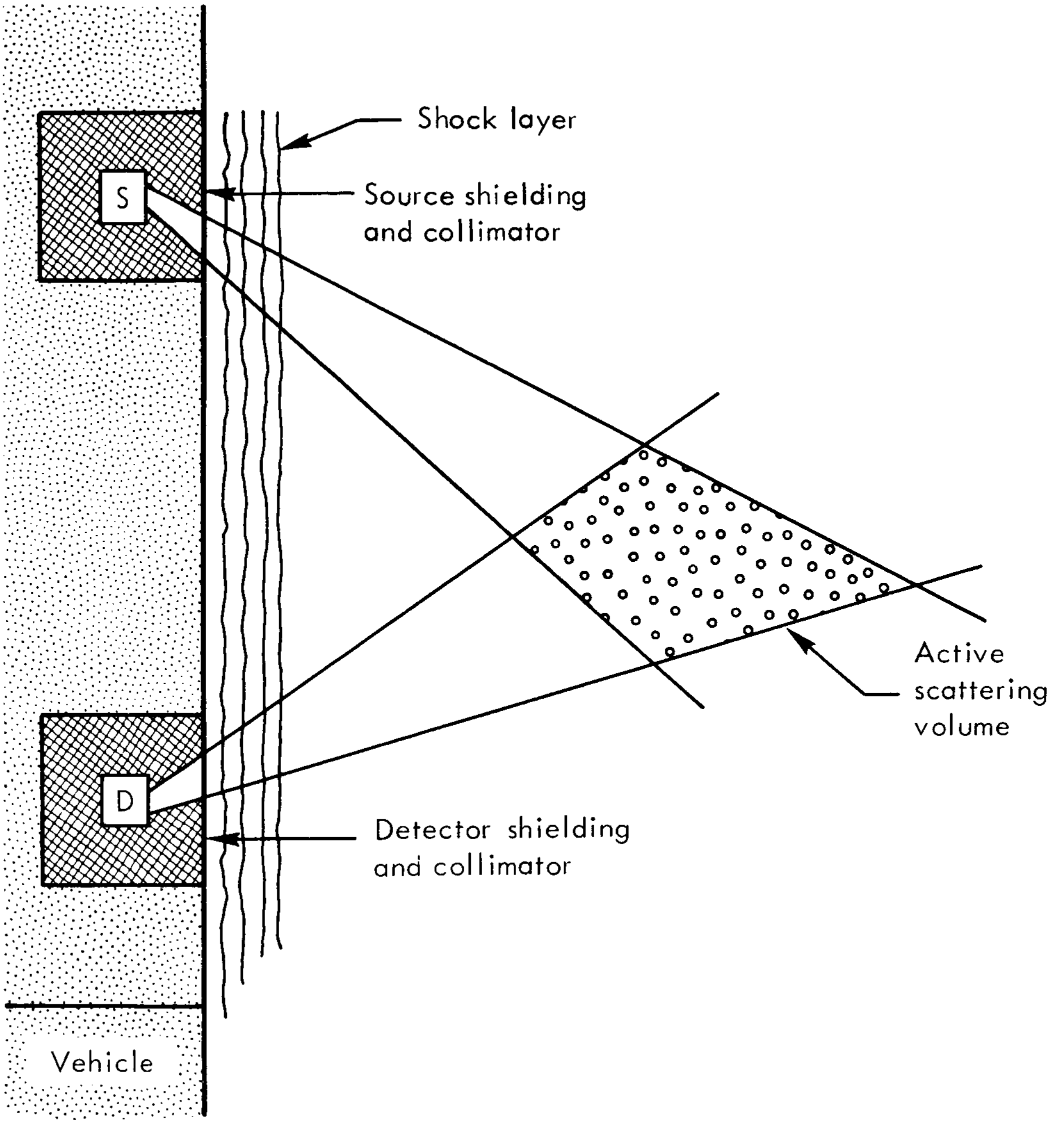

Fig. 7—A typical back-scatter gauge

IV. RELATED GAUGING MEASUREMENTS OF TERRESTRIAL ATMOSPHERIC DENSITY

Several studies have been made or are in progress concerning air density gauges, based on radiation principles for use in the earth's atmosphere. Work has included study programs, space chamber testing, and some flight testing. A review of this work is useful in considering techniques that may be suitable for the Martian atmosphere.

SMALL-ANGLE SCATTERING OF BETA RAYS

Early studies favored the investigation of beta-ray, small-angle scattering. In one such study in space chamber work, Rupp[10] used 0.2 curies of Sr^{90}, working in the approximate equivalent altitude range of 0 to 200,000 ft. The source and detector were separated by 78 inches. In this work the attenuation effect of absorption at altitudes less than 100,000 ft masked the scattering measurement. Above 100,000 ft, the interference of the direct beam also tended to mask the scatter effect, although these effects could be minimized by changes in geometry and improvement in the specific design of equipment.* Because this experimental setup had these errors, the data were not significant as a measure of the intensity of scattering. It was, however, not over 500 counts per second at the maximum value and would have been much less if the direct beam had not contributed. The interference effect of the direct beam produces a flux at the detector, which varies little with altitude or density.

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*Rupp's work with improved techniques, was continued by Richard Eskridge and was reported in "Atmospheric Density Measurement by Use of Radioisotopes," (thesis), Air University, USAF, Wright-Patterson Air Force Base, Ohio, GA/PHYS/63-4.

The study did, however, illustrate two significant causes of error in the small-angle scattering gauge. These were:

1. Attenuation at higher densities due to the low penetration of the beta particles

2. Interference of the direct beam at very small angles.

Work done at Parametrics,[11] considered the use of radioisotopes for measurement from balloons, in the limited range of 0 to 140,000 ft. Beta ray absorption was recommended for 0 - 45,000 ft range (using carbon-14) and small-angle scattering for the 45,000 - 140,000 ft range (using krypton-85). This study consisted of analysis and laboratory experiments. Subsequent flight tests were only partially successful because of equipment malfunction.[12] In a later work[13] they considered gauging at greater altitudes, (up to 250,000 ft) and at high-speed reentry. They concluded that a source of the order of 1000 curies of Pm-147 would be required to operate at 250,000 ft.

In a test that was a part of this investigation, a 1 millicurie source of Pm-147 was used, which yielded a scattering strength of 4.86 x 10^6 counts per second per gram/cm^3. The beta gauge using low-angle scattering, however, is not considered adequate for measuring ambient density because of the interference effect of the shock layer. It was suggested that the technique might be used for measurement of the density of the shock layer itself, if such is of interest. The report also suggested further areas of investigation: (1) a flush mounted back-scatter beta gauge for shock layer density measurement, and (2) the use of of an electron beam to generate secondary radiation in the form of X-rays, measuring the intensity of the X-rays thus produced as a measure of the concentration of atmosphere. This is recommended as a high-altitude technique in the range of 300,000 to 600,000 ft. Use of an electrical X-ray generator for altitudes in the range of 0 to 300,000 ft was also suggested.

A special geometry for the forward scattering technique was proposed by Falckenberg and Schumacher.(14) They suggested collecting all the forward scattered electrons, using a large area detector with an opening to pass the primary beam. This method would not be useful or would be at best ambiguous in high pressure ranges because of the absorption effect previously mentioned. Further, the instrumentation and alignment problems to prevent detection of any of the direct beam appear to be formidable in any flight version of such a method.

BACK-SCATTERING OF X-RAYS AND GAMMA RAYS

An early study(15) done by Giannini Controls Corporation considered all types of radiation gauging methods and came to the following conclusions:

1. Scattering techniques are preferred over transmission techniques because of the greater ability to measure ambient air density by minimizing the possible effect of shock waves.

2. Gamma radiation is preferred over alpha and beta radiation because no special windows are required in the vehicle, the scattering return is high, and high source strengths are available in suitable geometry.

3. Because of the large sources required, handling problems, and shielding weight requirements, measurement of air density at very high altitudes with gammas is not attractive.

In later work(16) Giannini conducted flight tests using a gamma source; 21.5 curies of Ce-144 was the source used in a test aboard a Nike-Apache rocket fired at Wallops Island in December 1963. The useful range appeared to lie between 0 and 180,000 ft altitude, for which 5 per cent accuracy appears feasible. Some of the limitations encountered are expected to be overcome in future tests using a 50 curie source and improved electronics, testing up to an altitude of 300,000 ft. The first tests resulted an a counting rate yield of approximately 1.2×10^7 counts per second per curie per gram/cm^3.

Giannini has also conducted feasibility tests on the X-ray back-scatter method in a space chamber environment.(17) The tests are preliminary and subject to refinement with improved X-ray source control and detector electronics. The preliminary results indicate a response rate of the order of 10^{10} counts per second per gram/cm^3. This rate was achieved at an X-ray tube current of 5 ma; the voltage was not known accurately, but is estimated at about 50 kilovolts. In the self-rectified, alternating current mode of operation, regulation of the high voltage transformer is poor, and measurement difficulties were encountered with the control circuit. Giannini suggested that the dc mode of operation and better control would increase the output by a factor of 5 to 10.

ELECTRON-BREMSSTRAHLUNG GENERATION

A very sensitive modification of the X-ray back-scatter technique is reported by Ziegler et al.(9) A primary source in the form of a low energy electron beam is directed to the ambient air volume. The electron beam interacts with the atoms contained in the gas volume, generating X-rays. These X-rays are emitted in all directions, but were specifically measured at right angles to the primary beam. In laboratory experiments this method yielded a high counting rate: 3.7×10^{11} counts per second per gram/cm^3 for an electron beam operating at 4 kilovolts and 100 microamps. Response was measured at pressures corresponding to earth altitudes of roughly 300,000 to 600,000 ft. The method was not intended to be used at lower altitudes since the higher density air would absorb most of the low energy electron beam and filament burnout would result in the presence of oxygen. During the measuring period, the electron beam is entirely open to the atmosphere. It is not practical to seal off the electron gun in a vacuum during operation because of the high absorption of any solid barrier material for the low voltage beam used. While higher voltages and differential pumping methods could be considered to extend the range, they would add greatly to the complexity and power requirements of the system.

ADDITIONAL TESTS IN PROGRESS

1. A 50-curie source (Ce-144 or Co-57) is to be used by Giannini Controls Corporation in further gamma back-scatter testing.

2. Giannini Controls Corporation is conducting pulsed X-ray back-scatter studies of air density for increased sampling rate.

3. Giannini Controls Corporation will conduct at White Sands balloon flights to altitudes of 100,000 ft using Sc-75 back-scatter sources. The tests are planned to also carry radiosonde instrumentation for comparison purposes.

4. Parametrics is using alpha absorption (straggling range) in measuring density--altitudes from 0 - 12,000 ft for use on aircraft.

5. Parametrics will test an 85 mc Pr-147 source in the 100,000 to 200,000 ft range. This is intended for dropsonde application. Accuracy is given as 5 per cent.

6. Parametrics will test the electron-X-ray scatter device described above in Nike-Cajun tests in 1965 in the range of 300,000 to 600,000 ft; 5 to 10 per cent accuracy is anticipated.

SCATTERING RESPONSE

One way to consider how the gauging methods will respond in Martian flights is to project the terrestrial test results. For this purpose, pertinent data was extracted from the foregoing tests and is summarized in Table 4. The test results are also projected in terms of a possible increase in source strength.

Table 4

RESULTS AND PROJECTIONS OF TERRESTRIAL ATMOSPHERE DENSITY GAUGING TESTS

	Experiment		Projection		
Method	Source	Rate (counts per sec per gm/cm^3)	Possible Source Increase	Rate Extension (counts per sec per gm/cm^3)	Estimated Response (for 10^{-8} gm/cm^3 in counts/second)
(Parametrics) Low-angle beta	1 mc Pm-147	4.8×10^6	1000 curies	4.8×10^{12}	4.8×10^4
(Giannini Controls) Gamma backscatter	21.5 c Ce-144	2.6×10^8	1000 curies	1.2×10^{10}	1.2×10^2
(Giannini Controls) X-ray backscatter	90 KV-5ma[a] X-rays	1×10^{10}	(b)	5×10^{10}	5×10^2
(Parametrics) Electron-bremsstrahlung	4 KV-100μa beam	3.7×10^{11}	1 ma beam	3.7×10^{12}	3.7×10^4
(Parametrics) X-ray backscatter	20 KV-5ma X-rays	8×10^7	(c)	2×10^9	20[c]

[a]The effective voltage in test is estimated in the 30-50 KV range because of alternating current mode of operation and unknown regulation and control variables in this particular test.

[b]Five to ten times improvement factor in use of direct current power source and controlled output.

[c]The measurements are part of work in progress on Contract AF 33(6150)-1288 for RT&D, AFSC, Wright-Patterson AFB and do not necessarily represent final results. The measurements were made in a space chamber using narrow angle X-ray and detector geometry. The factor of a 25 times increase is based on the use of a more divergent beam. It does not represent a full projection of the method and cannot be compared to the other X-ray measurement without considering differences in geometry, operating voltage, and power input.

V. GAUGING THE MARTIAN ATMOSPHERE

METHOD

Beta scattering does not appear to be a practical method for gauging the density of the Martian atmosphere because of its many inherent limitations. The low penetration of beta radiation limits its range of application because of the absorption effects at greater densities and the resulting ambiguities in output. The low scattering intensity at larger angles would indicate the use of small-angle scattering. However, under these conditions the shock layer absorption would produce very large errors. There would also be design problems since the source and detector would have to form a part of the vehicle surface, because any reasonable amount of vehicle skin would absorb all or a large part of the beta rays.

The source presents problems, too, as it would have to be very thin and consequently of a large area in order to prevent self-absorption. Very large sources present logistics problems--the ground crew must be protected during assembly and checkout. The decay of source strength with time creates difficulties in having the source availability coincide with launch time if delays in production, test, and launch occured. A further disadvantage in using a radioactive source is in its possible interference with other experiments on board during flight and the chance of contaminating the Martian surface in the event of a hard landing.

Gamma scattering is a more suitable method because of the greater penetration of the radiation and the more favorable back-scattering response. Gamma sources are reliable in accord with the radioactive decay process and do not require electrical power. However, in order to make measurements in time intervals of the order of one second, as would be needed to obtain the Martian density profile, the source strength required would be at least 1000 curies. This presents problems in design and application since large gamma sources are troublesome to handle, requiring shielding of hundreds or thousands of pounds for the protection of ground personnel. Although less shielding is required in flight, an appreciable weight will be required to keep the primary radiation from reaching the detector, since the unshielded source will emit radiation of equal intensity in all directions.

Another need for shielding large sources is the adverse effect that radiation has on components of the spacecraft. Over a period of several months in flight prior to the Mars encounter, the radiation dose could reach levels damaging to the electronic components and organic materials used in the craft.

The selection of suitable gamma sources is restricted by the long period of flight that requires that the half lives of the isotopes be of the order of several months. Low energy gamma radiation of approximately 100 KEV would be best suited to give a good back-scatter response. However, many isotopes have multiple radiations, and the presence of any higher energy components adds to the shielding problem. For example, Ce-144, which has a gamma radiation of .134 MEV, has several other radiations, including 0.94 MEV gammas that are highly penetrating. This would increase the shielding weight beyond that required for the desirable radiation.

In one test flight, a 21.5 curie source of Ce-144 was shielded by 35 lb of lead but nevertheless added appreciably to the background count. In addition, the problems of logistics, contamination, and interference discussed above for beta sources would be present and probably more severe.

X-ray backscatter (electrically generated) appears to be the most attractive radiation method for gauging the Martian atmosphere. The intensity levels obtainable are useful in the density range of 10^{-8}gm/cm^3 to 10^{-4}gm/cm^3 that is expected. The use of electrically generated X-rays offers the opportunity to control both energy level and intensity of the radiation by the appropriate selection of input conditions. The fact that there is no radiation present except during the actual operations keeps personnel hazard problems to a minimum during installation and checkout. Further, the absense of radiation will permit the best measurement of background and other radiation effects during space travel. Power will be required for the X-ray source, but since it is only of the order of 100 watts and required only during the period of entry, a battery or other energy sources should be practical. Another consideration in favor of the X-ray method is the fact that neither the incident beam nor the scattered radiation carries any charge. Accordingly, the presence of electric or magnetic fields in the atmosphere will not affect the scattering relationship. Furthermore, the scattering process is relatively independent of ionization within the gas volume being measured.

Electron-bremsstrahlung generation is recommended for application in the very low density range. Although the principal density measurements that will be required in the Mars probe will be in the range greater than

10^{-8} gm/cm^3, the opportunity to gain additional information in regions of lesser density with only a little increase in weight or power makes it attractive to include the electron source in the instrument package. A common X-ray detection system could be shared with the equipment used for the X-ray back-scatter in the greater density range.

Furthermore, both the X-ray and electron methods insure that there would be no contamination of the Martian surface with radioactive material in the event of the breakup of hard-landing vehicles.

THE DENSITY RANGE

In considering the gauging of atmospheric density, the region of density greater than 10^{-8} gm/cm^3 is of greatest interest since it is in that region that reentry heating takes effect and density becomes great enough to give appreciable lift to vehicles and other airborne bodies such as balloons and parachutes. The lesser density region at greater altitudes is of theoretical interest and is useful in orbital flight planning, but it is not considered as critical as the higher density region.

In general, the plausible range and even the upper and lower limits of the Martian atmosphere are not outside the range of densities for which instrumentation has been made or is under development for use in measuring the earth's atmosphere. Referring to Fig. 1 (p. 5), in which density is plotted as a function of altitude, we notice two significant factors:

1. The surface density of the Martian atmosphere is considerably less than for earth
2. The rate of change of density as a function of altitude is less for the Martian atmosphere.

These two factors favor measurements by the type of instrumentation considered since:

1. The range covered will not be as great as for earth
2. The lower rate of change will give better sampling conditions for establishing a density profile.

THE COMPOSITION RANGE

Little is known about the composition of the Martian atmosphere and the assumed values vary widely, as tabulated in Appendix B. In considering radiation scattering techniques for measuring density, the chemical elements contributing to the scattering will affect the net intensity. Assuming carbon dioxide, nitrogen, and argon as the probable principal constituents, the chief concern will be the argon content, since carbon, nitrogen and oxygen are adjacent elements in the periodic system, and hence have similar scattering cross sections. Argon, however, is several elements removed in the system.

Case I. Considering X-ray back-scatter at low energies and from lighter elements such as are present in a gaseous atmosphere, the strength of scattering will be a function of the number of free electrons in the active scattering volume.(18) The total number of scattering electrons will be the summation of the products of the number of free electrons per molecule and the number of molecules present for each constituent.

The number of free electrons per atom is equal to Z, atomic number. According to the gas laws, for any selected atmospheric density the number of molecules present will be inversely proportional to the molecular weight of the gas. In the case of argon, a monatomic gas, the molecular weight is equal to atomic weight, A, and the electron density will be proportional to Z/A. For diatomic gases such as nitrogen the molecular weight is 2A; however, the number of free electrons per molecule will be 2Z resulting in the same Z/A relationship. The same is true of a gas that is partially dissociated. Effective Z/A values for compounds and mixtures can be calculated using weight percentage composition values such as are contained in Appendix B.

The following values are calculated for constituents:

	Z	A	Z/A
C	6	12	0.50
N	7	14	0.50
O	8	16	0.50
A	18	40	0.45
CO_2	-	-	0.50

Considering contribution by weight per cent of constituents, the effective Z/A for atmospheres of interest are:

Earth's Atmosphere	0.50
Mars High N_2	0.50
Mars High A	0.46
Mars High CO_2	0.49

Composition is of little effect, even for the high argon model.

Case II. In the case of the electron-bremsstrahlung method, Ziegler[(9)] shows the Z^2/A dependence of the strength of scatter signal.

The effective Z^2/A for constituents and atmospheres of interest are:

C	3.0
N	3.5
O	4.0
A	8.1
CO_2	3.7
Earth's Atmosphere	3.7
Mars High N_2	3.6
Mars High A	7.0
Mars High CO_2*	4.5

Of these, only the Mars high argon atmosphere would lead to extreme errors, and in that case the intensities would be nearly twice those for a high nitrogen atmosphere, resulting in calculation of too high a density by the same factor. In application the error would be reduced by the fact that the electron-bremsstrahlung method is intended for low density range measurements at high altitudes. At such altitudes there is most likely lesser concentration of the heavy gases than found near the surface.

Absorption Effect. In addition to the above factors, composition can influence the amount of signal attenuation due to absorption and secondary scatter. Any such errors, however, are small--in most cases negligible--as discussed in Appendix C, and can be kept to a further minimum by the selection of proper operating voltages for the radiation source.

These considerations indicate that X-ray backscattering as proposed will yield density measurements that are relatively independent of composition. The electron-bremsstrahlung method, however, is more sensitive to composition. Obtaining simultaneous readings or alternating readings by the two methods in the transition range near

* High CO_2 atmosphere assumed to contain 20% argon also.

10^{-8} gm/cm^3 would serve to establish a correction factor for the electron-bremsstrahlung method. The flight package might also include instrumentation to measure composition either in flight or near the surface. Methods of compositional analysis will not be discussed in this study except for reference to alpha scattering,[19] mass spectrometry, and gas chromatography as some of the methods that have been suggested.

Another interesting possibility is the use of X-ray emission spectroscopy (X-ray fluorescence) to determine the composition directly during flight. In this method the primary X-ray or electron source excites characteristic radiation in the atmosphere. The radiation spectrum thus produced is analyzed qualitatively and quantitatively as a measure of composition.

INSTRUMENTATION

The Package.-- Table 5 shows estimates of the physical characteristics of possible gauging packages for terrestrial use.

Table 5

ESTIMATED CHARACTERISTICS OF POSSIBLE GAUGING PACKAGES

System	Weight (lb)	Volume (cu in.)	Power (watts)
Pulsed X-ray (grid controlled)	12	250	40
Pulsed X-ray (field emission)	18	400	60
Continuous X-ray	15	500	(batteries, 5 lb)
Electron-bremsstrahlung	15	360	30
Continuous X-ray combined with electron-bremsstrahlung	20	480	180

These values are given only as an indication of the range of values and should not be directly compared since: (1) they are projected and estimated values, and (2) the systems listed have not been normalized to be equally effective in making measurements.

It is reasonable that an X-ray backscatter gauge for a Mars mission could be constructed weighing 15 to 20 pounds. It would occupy a volume of about 400 cubic inches and require approximately 100 watts of power during the actual gauging period. Considering that the same detector system could be used, an electron source could be added with an estimated weight of 2 to 5 pounds, depending on whether a separate power supply is used. The added volume should not exceed 100 cubic inches with power requirements of about 10 watts.

The exact packaging and geometry of the gauging system can be varied to conform with the overall characteristics of the entry probe. Source and detector can be in separate packages but they must be mounted in constant and proper alignment. A source-to-detector separation of approximately two feet would insure that the active gauging area is outside the shock layer and would yield a usable scattering signal strength. (Appendix C contains shock layer effect calculations.)

The Source. The final selection of an X-ray source will be dependent upon the development and testing of prototype gauges. However, it is appropriate to consider factors that would influence the selection.

Three principal factors affect the choice of an operating mode: (1) the change in ambient density during the sampling period, (2) the statistical accuracy of the measurement of the scattered radiation, and (3) the data communication requirements of the measurements.

Taking these factors into consideration, a measurement period of the order of one second seems the most favorable. For such a sampling period, continuously operating X-ray tubes appear more satisfactory than pulsed tubes in terms of output and stability. (Appendix D discusses the selection of the sampling period and compares the outputs of pulsed and continuous tubes.)

Selection of the operating voltage for an X-ray back-scattering system is influenced by several factors. The output of an X-ray tube is radiation in a range of photon energies. The upper limit of photon energy is determined by the operating voltage. The lower limit is determined by the absorption of the tube envelope that maintains vacuum and permits passage of the X-rays, and by absorption effects in the outside medium and the detector. As the operating voltage of a given X-ray tube is increased, the efficiency of X-ray generation will increase in an approximately proportional rate in the voltage range of interest. The efficiency is the ratio of the watts of photon energy produced to the watts of power applied to the tube. The efficiency is also proportional to the atomic number of the target material in the X-ray tube, thus favoring the use of tungsten or platinum for this application.

The increased efficiency with increased voltage results in an increase of radiation at all photon energies in the range observed at lower voltage. In addition the higher voltage produces other photons of greater energy than previously observed. The distribution of energies will be a function of the above parameters plus those relating to the wave form of the high voltage circuit powering the tube. For example, a tube operating from an alternating current, high voltage source will be powered by a multiplicity of voltages during the cycle, each responsible for a spectrum of radiation energies. Consequently, the direct current mode of operation, or capicator smoothing of input voltage applied to the tube, tends to increase the efficiency and the proportion of higher energy radiations.

Typically the photon energy distribution will be maximized in the region of 1/2 to 2/3 of the maximum photon energy. The distribution of energies from a pulsed tube will be very sensitive to the wave form of the high voltage pulse applied.

In addition to the generation of continuous or bremsstrahlung radiation described above, X-ray tubes may emit characteristic radiation as a result of major energy level shifts within the target atoms. However, since the tubes used will have targets of a high atomic number and the voltages will not be appreciably above the minimum excitation potential for such radiation (Tungsten-59 kv, Platinum-67 kv for K-alpha characteristic radiation), the amount of such characteristic radiation will be relatively small.

The scattering effect will decrease with increasing photon energy in an orderly and known manner in accord with scattering laws (Appendix C). The density gauging suggested here utilizes the incoherent scattering and is not affected by the coherent scattering that is concentrated in the forward direction.

The photoelectric absorption effect is most pronounced at low voltages and for higher atomic number elements. However, even in the case of argon the absorption due to the photoelectric effect will produce little attenuation except for photon energies below 20 kv (Appendix C).

To summarize the selection of X-ray operating conditions there are certain factors to be considered.

Factors favoring high voltage are:

1. Increased efficiency of X-ray production
2. Decreased absorption in the tube envelope, vehicle skin, and shock layer
3. Less photoelectric absorption in the scattering medium.

Factors favoring lower voltage are:

1. Lesser high voltage insulation problem
2. Higher back-scattering.

Finalization of the operating package is a matter requiring engineering evaluation and testing. The voltage range between 20 and 100 kv appears of most practical use, with 80 kv a likely design point. Power to the X-ray tube of about 80 watts will produce usable intensities and would be a desirable design point in view of heat dissipation requirements. For a gauging system operating in a single mode in the range of 10^{-3} to 10^{-8} gm/cm^3, continuous source operation appears preferable to the pulsed mode.

The Detector

Several factors affect the accuracy of the measurement of radiation intensities. The three principle factors are:

1. The intensity of the radiation, in this case the scattered radiation reaching the active volume of the detector

2. The background intensity, which has several contributing sources: leakage from the primary source used in the density apparatus, from other equipment on board, and the outside contribution from cosmic or solar radiation

3. The threshold, linearity, and saturation characteristics of the detector.

The first two factors are more directly related to the output of the radiation source and the geometry of the gauging system than to the detector proper. However, they indicate the necessity of measuring background, which is best accomplished with a second detector located so as not to receive the atmospheric scatter, but to detect stray radiation from the source as well as the cosmic background. Alternatively, if a proven source of very low or known background is used after proper calibration in the earth's atmosphere, the second detector could be omitted and the background measured with the source off. The necessary arrangement would have to be determined experimentally, using the actual gauging system and its geometry. The statistical nature of radiation and the effect of background on determination accuracy is discussed in Appendix E.

With an X-ray tube operating at 80 kv and 1 ma tube current, it is expected from preliminary tests in the earth's atmosphere that a scattered intensity of the order of 100 counts per second would result in a density of 10^{-8} gm/cm^3. For the Martian surface density, the counting rate would be expected to be 10^6 counts per second or higher but probably not over 10^7 counts per second. It is believed that the electron-bremsstrahlung scattering apparatus could be constructed to yield intensities in the same range, in the density range of 10^{-12} to 10^{-8} gm/cm^3.

Photomultiplier tubes are sensitive detectors and cover a wide range of counting rates, up to the order of 10^8 counts per second. They are currently in use for other space applications and should have the proven reliability to accomplish the measurements necessary in the Martian probe.

Solid state detectors offer a means of detecting high intensity short-time bursts of gamma radiation and would prove useful if pulsed techniques were employed.

Output Information

The type and quantity of output information will depend upon the nature of the detector circuits used. However, most typically, pulses are produced and scaled to a lesser value by the use of several stages of binary scaling. The necessary data rates to send this information back to earth or to an intermediate space vehicle will be a function of the range of data and special factors of change in source intensity, either programmed or responsive. One approach to determining data requirements of the output of the sensor is to consider the counting range of 10^2 to 10^7 counts per second and a counting interval of one second. If all counts were to be stored in the binary registers, 23 registers would be required. To read data out with a precision of the order of 1 part in 100, it would be necessary to read out the seven most significant registers for the particular count. However, to cover the entire range, there would be sixteen possible groups of seven consecutive registers. Carrying this information would require 4 additional registers ($2^4 = 16$) for a total of 11 bits for the signal. The background count would be lower, requiring an estimated 9 bits. One signal and background reading per second would require a bit rate of 20 bits per second.

Other techniques of readout are possible, such as transmitting frequency information from selected registers or operating on a predetermined count basis. However, ranging is required in this case and a certain basic bit rate is necessary to achieve the desired degree of accuracy. Such other methods also indicate a rate of 20 bits per second necessary to carry the required information for 1 determination per second. One improvement that has been suggested[19] is the use of square root converters in the counting circuits. With only a slight increase in error over the statistical error, the number of bits can be reduced by a factor of 2. As a method of reducing bit rates further, if necessary the background could be read less frequently.

Since at high counting rates more counts will be accumulated in a one-second interval than are necessary for reasonable statistical accuracy, it would be possible to count for lesser time or to time a fixed total count. Such methods would require additional flexibility in the system, either programmed or responsive, since longer times would be needed for the low response from areas of low atmospheric density. Because of the remoteness of the experiment in the Martian atmosphere, the equipment should be designed to operate with an absolute minimum of such ranging or mode changing.

EXPECTED ACCURACY OF GAUGING

The accuracy of the density determinations will be influenced by the following factors, which have been previously discussed:

1. Accuracy of intensity measurement
2. Variation in composition of scattering medium
3. Density changes during the sampling period.

Additional factors are related to the equipment:

1. Stability of the radiation source
2. Stability and response of the detector.

Considering the present state of experimental work and the possible improvements in techniques and construction, the following accuracies appear feasible for gauging the Martian atmosphere by the radiation method.

Density in gm/cm^3	Method	Accuracy Range
10^{-12} to 10^{-8}	Electron-brems-strahlung scatter	10 to 20%
10^{-8} to 10^{-7}	X-ray scatter	10 to 20%
10^{-7} to 10^{-3}	X-ray scatter	5 to 10%

It should be recognized that the above values of accuracy are estimated for a system operating under dynamic conditions of Martian flight as contrasted to a laboratory situation in which 1 per cent accuracy might be attainable. Further, the selection and refinement of entry modes can improve the accuracy. For example, if by control of flight mode, the vertical descent rate were as low as, say 2000 to 3000 feet per second, then in the 10^{-8} to 10^{-7} gm/cm^3 density region, accuracy could be improved. By allowing a longer time for measurement or by giving an increased number of determinations, the accuracy could be within the 5 to 10 per cent range stated for the region of greater density.

VI. RECOMMENDED AREAS OF DEVELOPMENT

This section suggests some areas of research and development for optimizing the radiation gauging method for use in the Martian atmosphere. Certain engineering aspects of instrumentation development and testing are also stressed as those most critical to the successful operation of the system under Martian flight conditions.

Optimization of Operating Conditions

A critical experimental investigation should be made of the optimal X-ray operating voltage for the backscatter density gauging method. This would include study of scattering intensity as a function of voltage, power input, and power supply wave form. To date, work with similar systems has been in the low voltage range of 5 to 20 kv and in the higher voltage range of 80 kv and above. While analytical considerations tend to favor operation in the higher voltage range, it is important that the entire range be carefully investigated experimentally to find the point of optimal scattering response. This is important because operation at higher voltages requires more attention to insulation problems and must be fully justified in terms of higher intensities yielding increased accuracy of range of the apparatus. An evaluation of the power supplies must also be made in terms of reliability of operations, which is the most important criterion for Martian flight.

Range Extension

The electron-bremsstrahlung method should be evaluated more extensively to determine optimal operating conditions and the feasibility of range extension to overlap with the X-ray backscatter method. This overlap would apply in the critical range of 10^{-8} to 10^{-7} gm/cm^3 in which the X-ray response is low. The use of higher voltages and currents may be practical for the operation of the electron beam in that density range, considering that the Martian atmosphere is probably lacking in oxygen. This would lessen the problems of filament burnout and cathode poisoning that are encountered in the terrestrial atmosphere at similar densities.

Pulsed X-Ray Applicability

Although at the present state of development pulsed techniques do not appear as attractive for gauging the Martian atmosphere as do conventional X-ray sources, it must be considered that this evaluation is made in terms of a relatively long permissible sampling period of the order of one second. If the need should arise for more rapid sampling, or if sufficient technological advances are made in pulsed techniques, then their use could become more attractive. For this reason some further investigation of pulsed techniques on an experimental basis is warranted to provide an alternate method.

X-Ray Spectroscopy

The analysis of the Martian atmosphere by X-ray emission spectroscopy, which has not been covered in this study, is attractive in that composition data and density data could be obtained simultaneously. The radiations characteristic of the atmospheric constituents are, however, of long wavelength and low penetrating power, thus requiring careful investigation of techniques and instrumentation suitable for reliable unattended operation. Such methods are not as simple and not as well advanced in development as the density gauging procedures but are attractive as an area for research, perhaps oriented to later flights.

Source Power Considerations

Since the Martian flight will require that the X-ray tube be energized after several months of in-transit flight, the switching circuits must be reliable. The circuits should also be capable of protecting the tube and the power supply from failure due to any shorting that could occur following the inactivation period. A getter system in the X-ray tube for removing any accumulated gases is also advisable. Operation of the X-ray tube at a low level of output during the flight, which would conserve power while keeping the tube in operating condition, should also be considered. Transit during several months and operation of the high voltage equipment in a vacuum environment require special consideration of insulation materials. Conductive paths outside the tube that might lead to high voltage discharge must be eliminated. The use of solid potting compounds appears desirable.

Radiation Detectors

The detectors must function properly over a wide range of scattered intensities. In addition it may be necessary and advisable to develop ranging methods for the source to keep intensities within detectable and recordable levels. Advances in discrimination circuits to reduce the background count will be helpful in increasing the accuracy of density determination. Mechanical X-ray filters may also be advantageous in ranging and in discriminating against unwanted radiation.

Related Terrestrial Investigations

It is important that tests in the earth's atmosphere be used to evaluate the accuracy and reliability of both the method and particular hardware systems that are developed. Such tests will also provide the necessary calibration data better than tests done in space chambers where wall effects prove troublesome.

VII. CONCLUSIONS

The purpose of this study was first to evaluate radiation gauging methods as they could be applied during entry of an unmanned probe to measure the density of the Martian atmosphere, and, secondly, to point out which of these methods appears best suited for early flights.

Except for its remoteness and the unknown factors in composition, the Martian atmosphere presents a gauging problem quite similar to that of gauging the density of the earth's atmosphere from a rapidly moving vehicle. Therefore, we have based our evaluation on projections and estimated of radiation gauging techniques currently used in the terrestrial atmosphere.

Of the several radiation gauging techniques now available, the use of X-ray backscattering with an electrically generated, continously operating, source of radiation appears to be the most promising for gauging the density of the atmosphere in the 10^{-8} to 10^{-3} gm/cm^3 range. X-ray backscattering has certain definite advantages:

- High intensity, yielding higher scatter count and better statistical accuracy
- An easily controlled on-off mode, requiring no shielding for the ground crew during inoperative periods
- No possible radiation contamination of the Martian surface
- Minimal shock layer interference
- The energy level of the source is easily tailored to the method since input is continuously variable
- The radiation source can be turned off completely so as not to interfere with measurements of other radiation effects
- The shielding weight for stray radiation is minimized.

Use of an electron beam, generating soft X-rays (bremsstrahlung), is recommended as an auxiliary technique for gauging in the range of 10^{-12} to 10^{-8} gm/cm^3, with a possible extension to 10^{-7} gm/cm^3, which would overlap the X-ray range.

At the present time we can make the following estimates for the X-ray gauging package:

Weight	15 to 20 lb
Volume	400 cu in.
Power	100 watts
Data rate	20 bits per determination; one determination per second

The inclusion of the electron beam source in the package would add:

Weight	2 to 5 lb
Volume	100 cu in.
Power	10 watts
Data rate	20 bits per second*

Gauging accuracy will be influenced by the selection of the flight mode because of the effect that vertical velocity has on the change of density during the sampling and measurement period. The particular instrumentation design will also affect accuracy because of its influence on the strength of the response signal. At the present state of development, the following accuracies appear realistic for radiation gauging of the Martian atmosphere in unmanned flight:

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*It is not expected that the two methods would have simultaneous output except perhaps in the range of 10^{-8} to 10^{-7} gm/cm^3.

Density (gm/cm^3)	Method	Accuracy
10^{-12} to 10^{-8}	Electron-bremsstrahlung	10 to 20%
10^{-8} to 10^{-7}	X-ray backscattering	10 to 20%
10^{-7} to 10^{-3}	X-ray backscattering	5 to 10%

Certain areas of research must be more fully investigated before a final choice of a gauging system can be made. These include the determination of the optimal X-ray operating voltage as well as a possible extension of the range of the electron-bremsstrahlung method and further study of pulsed techniques. In addition, in relation to the engineering aspects of the design and testing of gauging systems, further work needs to be done in testing X-ray operating reliability after the transit period, high voltage insulation methods, and the adequacy of detector and source ranging. It should further be stressed that testing in the earth's atmosphere is most important to determine the reliability and accuracy of techniques.

Although it is not a prerequisite to successful density gauging, the investigation of X-ray emission spectroscopy could prove useful to permit a possible simultaneous determination of atmospheric composition and density.

Continued work on terrestrial atmospheric density gauging should contribute significantly to the Martian effort. It is important, however, that additional programs directly oriented to the Mars mission be initiated.

Appendix A

ATMOSPHERIC MODELS

The following ranges of atmospheric density values have been used in considering the problem of density gauging by radiation methods.

Martian Atmospheres as Compared to Earth Atmosphere[a]

ALT KM	ALT (K ft)	Density (gm/cm^3)				
		10 mb[b]	20 mb	85 mb	133 mb	U.S. Std. Atmosphere
0	0	1.82×10^{-5}	3.634×10^{-5}	1.186×10^{-4}	1.49×10^{-4}	1.225×10^{-3}
2	6.6	1.64	3.289	1.098	1.40	1.007
4	13.1	1.48	2.965	1.015	1.31	8.194×10^{-4}
6	19.7	1.33	2.661	9.351×10^{-5}	1.22	6.601
8	26.3	1.19	2.377	8.596	1.14	5.252
10	32.8	1.06	2.111	7.879	1.06	4.135
14	45.9	8.19×10^{-6}	1.637	6.420	8.71×10^{-5}	2.779
18	59.1	6.17	1.233	5.181	7.13	1.217
22	72.2	4.04	8.084×10^{-6}	4.135	5.84	6.451×10^{-5}
26	85.3	2.65	5.294	3.260	4.78	3.426
30	98.4	1.73	3.463	2.536	3.92	1.841
40	131.2	1.10	2.192	1.143	2.38	3.996×10^{-6}
50	164.0	2.04	4.071×10^{-7}	5.175×10^{-6}	1.44	1.027
60	196.9	6.90×10^{-8}	1.379	2.354	8.76×10^{-6}	3.059×10^{-7}
70	229.7	2.32	4.633×10^{-8}	1.076	5.24	8.754×10^{-8}
80	262.5	7.72×10^{-9}	1.543	4.939×10^{-7}	3.11	1.999
90	295.3	2.55	5.098×10^{-9}	2.278	1.30	3.170×10^{-9}
100	328.1	8.35×10^{-10}	1.669	1.055	9.14×10^{-7}	4.974×10^{-10}
110	360.9	2.71	5.414×10^{-10}	4.911×10^{-8}	5.91	9.829×10^{-11}
120	393.7	8.70×10^{-11}	1.740	2.295	3.82	2.436
130	426.5	2.77	5.540×10^{-11}	1.077	2.47	7.589×10^{-12}
140	459.3	8.74×10^{-12}	1.747	5.080×10^{-9}	1.73	3.394
150	492.1	2.73	5.453×10^{-12}	3.494	1.17	1.836

[a]The sources for the atmospheric models are: 10 mb, Ref. 3; 20 mb, Ref. 20; 85 mb, Ref. 20; 133 mb, Ref. 21; U.S. Std. Atmosphere, Ref. 22.

[b]The 10 mb data are set as a lower limit based on the projection of Kaplan et al.,(3) of a possible 10 mb lower limit for the surface pressure of the Martian atmosphere. A pressure that low would represent an atmosphere of very unusual composition, e.g., 60 per cent CO_2, and would not lend itself to extension to greater altitudes by the method used for models of higher pressure.(7) To establish the 10 mb data as a possible lower limit, it has been assumed that the altitude-density function would follow the Schilling 20 mb atmosphere. All densities for the 10 mb model have been taken as one-half the Schilling 20 mb values. While not a rigorous solution, these values form a reasonable lower limit for densities to be encountered in the Martian atmosphere.

Appendix B

COMPOSITION OF SOME PROPOSED MARTIAN ATMOSPHERES

MARS-10 mb[3]

	mb	Mol Fraction	M. W.	Wt/Mol	Wt%
CO_2	6	.6	44.010	26.406	66.0
A	2	.2	39.944	7.988	20.0
N_2	2	.2	28.016	5.603	14.0
			Mol Wt =	39.997	100.0%

MARS-25 mb[3]

	mb	Mol Fraction	M. W.	Wt/Mol	Wt%
CO_2	4	.16	44.010	7.05	17.8
A	19	.76	39.944	30.35	76.5
N_2	2	.08	28.016	2.24	5.7
			Mol Wt =	39.64	100.0%

or

	mb	Mol Fraction	M. W.	Wt/Mol	Wt%
CO_2	4	.16	44.010	7.05	22.4
A	2	.08	39.944	3.19	10.1
N_2	19	.76	28.016	21.29	67.5
			Mol Wt =	31.43	100.0%

MARS-40 mb[3]

	mb	Mol Fraction	M. W.	Wt/Mol	Wt%
CO_2	3	.08	44.010	3.52	10.1
A	19	.47	39.944	18.77	53.8
N_2	18	.45	28.016	12.61	36.1
			Mol Wt =	34.90	100.0%

or

	mb	Mol Fraction	M. W.	Wt/Mol	Wt%
CO_2	3	.07	44.010	3.08	10.4
A	2	.05	39.944	2.00	6.7
N_2	38	.88	28.016	24.65	82.9
			Mol Wt =	29.73	100.0%

MARS-85 ± 4 mb(1)

	Mol Fraction	M. W.	Wt/Mol	Wt%
CO_2	.3	44.010	.13	.5
A	1.2	39.944	.48	1.7
N_2	98.5	28.016	27.60	97.8
		Mol Wt =	28.21	100.0%

EARTH-AIR

N_2	.7809	28.016	21.878	75.53
O_2	.2095	32.000	6.704	23.15
A	.0093	39.944	.371	1.28
CO_2	.0003	44.010	.013	.04
		Mol Wt =	28.966	100.00%

Appendix C

ABSORPTION AND SCATTERING EFFECTS FOR X-RAYS

The total attenuation of X-rays by matter is a combination of several effects:

1. Coherent scattering in which the energy of the photon remains the same but the direction is changed
2. Incoherent scattering in which the scattered photon has lesser energy and is also changed in direction
3. Photoelectric absorption in which the photon is entirely absorbed with release of an electron causing ionization
4. Pair production in which an electron-positron pair is produced. This occurs only at photon energies in excess of one million electron volts and has no effect in the gauging application.

The effects above are additive to produce the Total Absorption Coefficient. The relative intensities of the effects are functions of the photon energy and atomic number of the scattering element. The following tabulations in the range of interest in the gauging application have been abridged and recalculated from a standard reference[23]. All cross sections have been expressed in cm^2/gm to facilitate comparison with the total absorption coefficient.

NITROGEN

Photon Energy KEV	Coherent Scattering (cm^2/gm)	Incoherent Scattering (cm^2/gm)	Photoelectric Absorption (cm^2/gm)	Total Absorption Coefficient (cm^2/gm)
10	.193	.193	3.41	3.80
20	.060	.186	.353	.60
30	.029	.180	.092	.301
40	.017	.174	.035	.226
50	.009	.169	.016	.194
60	.007	.164	.009	.180
80	.005	.156	.003	.164
100	.004	.148	.002	.154

ARGON

Photon Energy	Coherent Scattering	Incoherent Scattering	Photoelectric Absorption	Total Absorption Coefficient
10	.67	.17	64.5	65.4
20	.255	.168	8.46	8.88
30	.124	.162	2.47	2.76
40	.081	.157	.973	1.21
50	.053	.152	.477	.682
60	.039	.148	.272	.459
80	.021	.140	.110	.271
100	.015	.134	.054	.203

Examining the tabulations we note:

1. The photoelectric absorption is much greater for the higher atomic number element.
2. With increasing voltage the incoherent scattering becomes the principal factor of attenuation.

In the gauging application the incoherent scattering cross section is the critical term in considering scattering response. The other effects and incoherent scattering outside the active volume will produce attenuation of the incident beam and attenuation of the scattered radiation within the angle of detection. The net result of such processes can be considered to decrease the response according to the absorption equation

$$I/I_o = \exp^{-\frac{\mu}{\rho}\rho x}$$

in which

I_o = Incident intensity

I = Transmitted intensity

$\frac{\mu}{\rho}$ = Mass absorption coefficient (cm^2/gm)

ρ = Density of absorbing medium (gm/cm^3)

x = Path length in cm

The absorption will be very small in the system under consideration except for argon at very low voltage. The quantitative effect of absorption is calculated below.

Shock Layer Effects

In considering the backscatter gauging method it is appropriate to calculate the possible attenuation due to absorption of the incident beam and the scattered radiation in the shock layer.

For the calculation the following conditions are assumed:

1. A source-to-detector separation distance of 24 inches
2. Backscatter at 120^{o}
3. A shock layer density 6 times ambient
4. A shock layer thickness of 3 inches

Figure 8 illustrates the geometry of scattering under shock layer conditions. The beam will be divergent but considered as an average effect centered about the scattering center shown. The total distance the radiation will travel is 48 inches or 122 cm. The effect of shock layer absorption is to increase the total effective path length. The actual distance traveled in one thickness of shock layer is $3''/\cos 30^{o}$ = 3.45". The effective path in shock layer will be 6x2x3.45 in. or 41.5 inches. The path length in ambient atmosphere will be 2(24-3.45) = 41.1 inches. Total effective path length is 82.6 inches or 210 cm in the case involving shock layer.

The shock layer absorption effect will be related to the attenuation of 210 cm of ambient atmosphere as compared to a 122 cm path length.

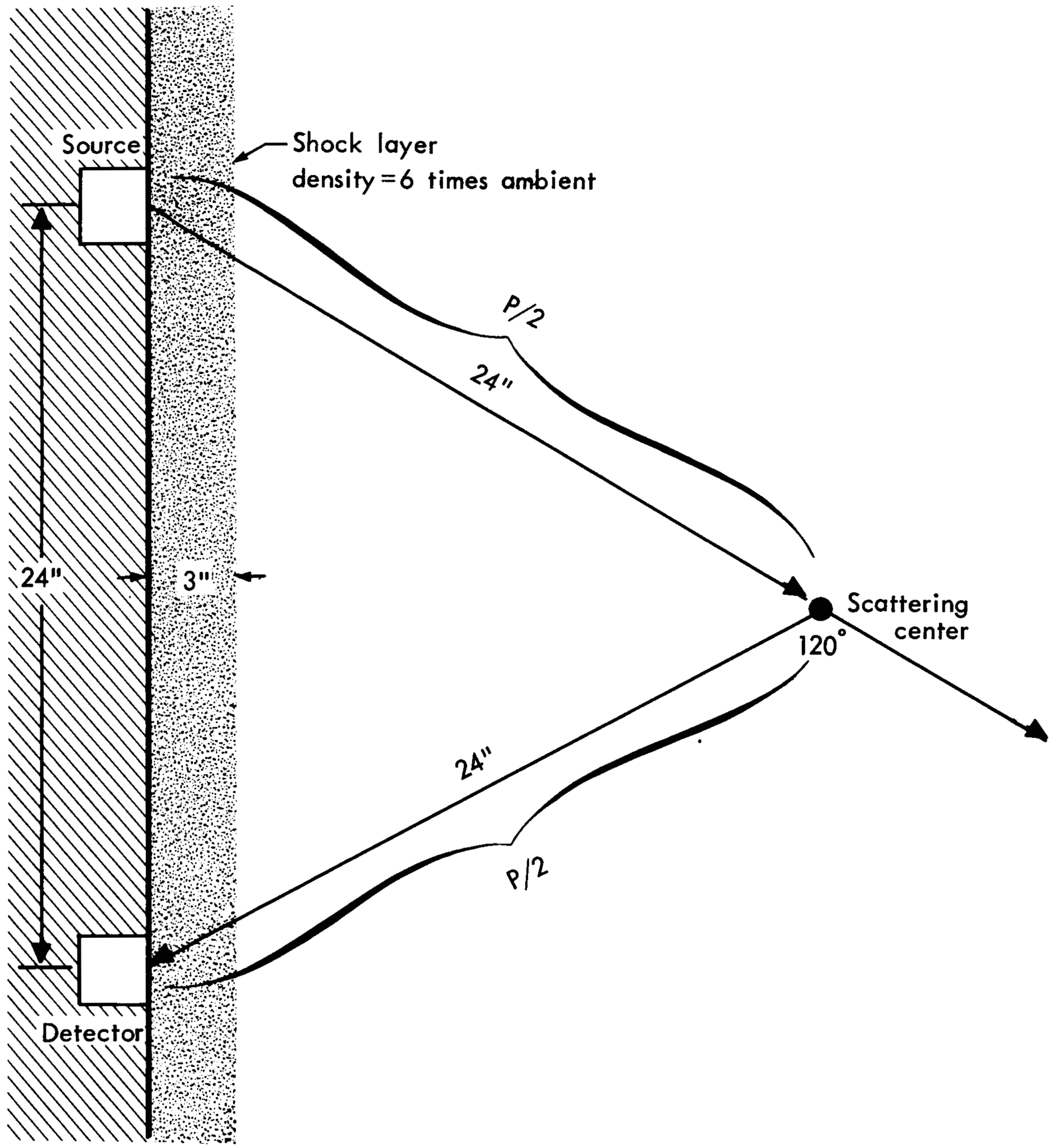

Fig. 8—X-ray back-scattering under shock layer conditions

Values of $\frac{\mu}{\rho}$ for elements of interest are tabulated below[22]

MASS ABSORPTION COEFFICIENTS

μ/ρ (cm^2/gm)

Photon Energy	C	N	O	A
80 KV	.161	.164	.168	.271
60 KV	.174	.180	.189	.459
50 KV	.185	.194	.208	.682
20 KV	.429	.600	.842	8.88
10 KV	2.28	3.80	5.93	65.4

Mass absorption coefficients for mixtures are calculated by the summation of individual coefficients multiplied by weight fractions.

MASS ABSORPTION COEFFICIENTS

μ/ρ (cm^2/gm)

Photon Energy	deVaucouleurs-85 mb (High Nitrogen)	Kaplan-25 mb (High Argon)
80 KV	.167	.246
60 KV	.187	.394
50 KV	.202	.569
20 KV	.742	6.95
10 KV	4.85	51.2

For a very worst case condition, consider radiation of 10 KV and the Kaplan high argon atmosphere at an ambient density of 10^{-5} gm/cm^3.

For non-shock layer conditions (122 cm path length)

$$I/I_o = \exp^{-51.2 \times 10^{-5} \times 122} = .94$$

For shock layer conditions (210 cm effective path length)

$$I/I_o = \exp^{-51.2 \times 10^{-5} \times 210} = .89$$

The effect of the shock layer is an absorption of only 5% over that of non-shock layer conditions

The very worst case is not likely to be encountered in flight. As a more reasonable case consider an element of radiation having an initial energy of 60 KV. The scattered radiation will have less energy, of the order of 50 KV[24]. Consider a high nitrogen atmosphere at an ambient air density of 10^{-6} gm/cm^3.

<u>For non-shock layer conditions</u> (Incident beam path = 61 cm, scattered beam path = 61 cm)

$$I/I_o = (\exp^{-.187 \times 10^{-6} \times 61})\ (\exp^{-.202 \times 10^{-6} \times 61})$$

$$= (\exp^{-.000011})\ (\exp^{-.000012})$$

$$= (\exp^{-.000023}) = .999 +$$

<u>For shock layer conditions</u> (Incident beam path = 105 cm, scattered beam path = 105 cm)

$$I/I_o = (\exp^{-.187 \times 10^{-6} \times 105})\ (\exp^{-.202 \times 10^{-6} \times 105})$$

$$= (\exp^{-.000020})\ (\exp^{-.000021})$$

$$= (\exp^{-.000041}) = .999 +$$

The difference in absorption due to shock layer is a negligible fraction of the incident intensity.

It must be recognized that the incident X-ray beam will be a continuous spectrum of energies as will be the scattered beam. Also, the scattered beam will be only a small fraction of the intensity of the incident beam. However, the simplified calculations as done here show clearly that the loss of intensity due to the higher density of the shock layer will not be significant.

Appendix D

A DISCUSSION OF PULSED X-RAY TUBES

In a comparison of pulsed and continuous X-ray tubes as applied to Martian atmospheric density determination, it is appropriate also to consider other constraints on the measurement period. Such factors include: (1) the change in ambient density during the sampling period*, (2) the statistical accuracy of measurement of the scattered radiation**, and (3) the data communications requirements of the measurements.***

For example, consider a vertical descent rate of 5000 ft per second in an atmosphere corresponding to the 20 mb model and at an altitude where the density is 10^{-8} gm/cm^3. For a continuously operating tube (80 KV - 1 ma), a scattered intensity of 100 counts per second is anticipated. During a one-second sampling period, the density change would be 20 %, but since the density profile is considered a smooth function, such a change should not introduce a large degree of uncertainty in selecting an average value. On the other hand, if the sampling period were 5 seconds, the vertical travel would be 25,000 ft and the density change over 100 %. The selection of a meaningful average value for this longer determination would be more uncertain and details of the profile might be lost. The sampling period of one second would record 100 counts, for which the relative probable error of the determination would be 10 % (assumed background/total ratio of 0.2).

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*See Fig. 1, p. 5 and Fig. 2, p. 9.

**See Appendix E.

***See discussion of output information, page 41.

Increasing the sampling time to 5 seconds would decrease the relative probable error to 4 % but would introduce the sample uncertainty discussed above. Using a sampling period much shorter than one second would result in a much greater statistical error. Finally, the communications rate is an important factor. A 20-bit output per determination is expected. At one determination per second the bit rate would be 20 bits/second, a rate which appears consistent with Martian communications and the needs of other devices carried on the vehicle. Shorter sampling periods, which imply greater sampling rates, would increase the bit rate requirements. These can be questioned because of the limited value of additional data points.

Pulsed X-ray tubes have been developed that give very high-intensity short-duration pulses. One example is a grid-controlled pulsed tube that operates at 80 kilovolts with 20 amperes tube current. The radiation is emitted in 10 nanosecond pulses with repetition rates up to 35 kc possible, but with tube life of only seconds at that high rate. Another technique is the field emission tube which utilizes a point discharge rather than filament emission. A typical tube would operate at 100 kilovolts and 1500 amperes tube current with 100 nanosecond pulses. The total tube life is estimated at 30,000 pulses. It can be pulsed up to 25 pulses per second but requires 4 minutes of cooling after 4 seconds of operation. It could operate at a reduced pulse rate without the cooling period and improvements in cooling are currently under investigation.

Pulsed sources have the advantage of making measurements possible in a very short time at higher densities. They also raise the effective rate over background. For example, if a pulsed tube were made to operate at a current 100 times that of a continuous tube, the scattered radiation flux should also be 100 times as great. The ratio of the signal to the natural background should also increase by the same amount. This advantage is offset by (1) the fact that system background rate due to leakage and spurious scatter will also increase proportionally and (2) since the pulse is short, fewer total counts will be accumulated during the measurement, decreasing the accuracy of determination. As an example, the output of the X-ray tube, at comparable voltages, can be rated in terms of ma-sec and the scattered signal will be directly proportional to this. A 1 ma continuous tube during a sampling period of 1 second will have an output of 1 ma-sec. The output during a single pulse of the grid-controlled tube described above is 2×10^{-4} ma-sec. It would take 5000 pulses to produce a quantity of radiation equivalent to the continuous tube. In the field emission tube described, the output per pulse is 0.15 ma-sec. Seven pulses would be required for the 1 ma continuous equivalent. While adequate counts might result from pulsed techniques in regions of greater density, the continuous method would appear more favorable in regions of lesser density.

Some pulsed techniques are not efficient in the use of input power. For example, the field emission tube utilizes a surge generator to provide the high voltage pulse. In operation, one half of the applied energy in the pulse is lost in a resistor network outside the tube and does not generate useful X-rays. Furthermore, since the method depends upon point discharge and field breakdown, consistent output from pulse to pulse is not assured.

Appendix E

THE STATISTICAL NATURE OF RADIATION INTENSITIES

The emission and detection of radiation is by nature a random process. The practical application of radiation density gauging will consist of making a series of single measurements of pulse effects. The counting techniques have been described in the literature.[25-26] The common factor of evaluation is the Relative Probable Error. This is expressed as P. E. = $.6745\sigma$, in which σ is the standard deviation. The resulting useful expression is P.E. = $\frac{.6745}{\sqrt{n}}$, in which n is the number of pulses observed. If determinations are made for the same period of time, the accuracy will be a function of the square root of the pulse rate.

The relative probable error corresponds to 50 per cent confidence limits; that is, a relative probable error of 1 per cent indicates that in one-half of the determinations made, the value will be within 1 per cent of the mean value.

Background

The scattered radiation signal will normally be superimposed on a background level due to the effects mentioned above. To determine the net signal, it is desirable to measure the background independently; for example, with a second detector positioned so as to not record the scattered radiation. The determination of both signal and background is subject to error, and the standard deviation of the difference or net count due to scattering will be equal to the square root of the sum of the squares of the standard deviations of the two determinations according to established statistical procedure.

The total count is a function of the counting rate multiplied by the time of count. For the instrumentation involved, we will consider that the total effect and background are counted for the same period of time. The relative probable error as a percentage of the count due to scattering will be

$$\% \text{ P.E.} = \frac{67.45(N_t + N_b)^{1/2}}{(N_t - N_b)}$$

in which

N_t = number of counts for total count rate

N_b = number of counts for background count rate

Since the accuracy is related to the total count, it will be necessary that counting rates be high if determinations are to be made over short time intervals. Furthermore, high effective rates will tend to increase the ratio of signal to background and will decrease the error due to the presence of background.

Figure 9 solves the probable error equation graphically and illustrates the effect of high counting rate in decreasing error. If one second is used as a measurement time, then the total count can also be read as counts per second. If, for example, a relative probable error no greater than 1 per cent is desirable, counting rates must be over 4000 counts per second and the requirements increase beyond this value as the background ratio increases.

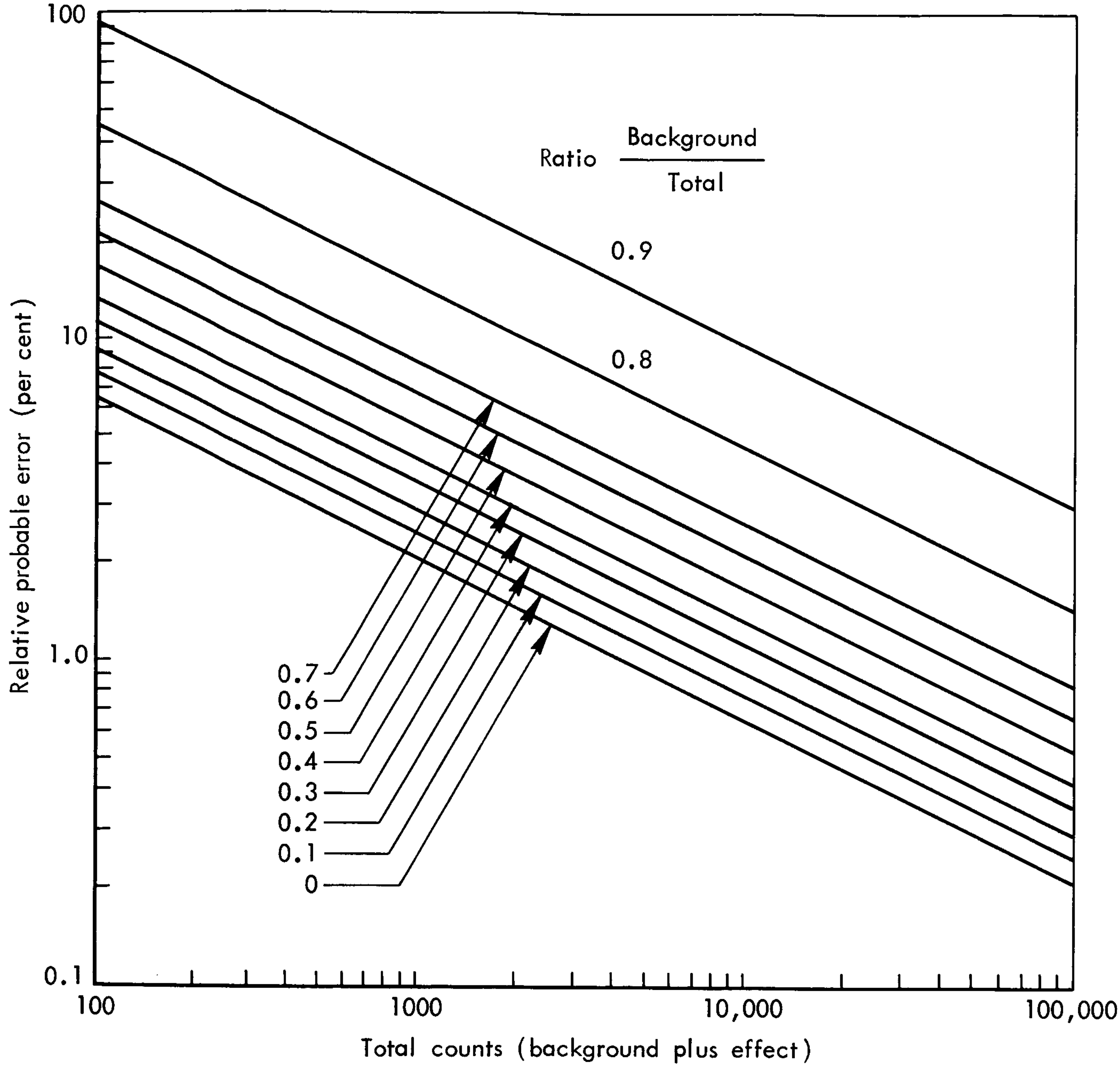

Fig. 9—Probable error as a function of total count and background

Appendix F

SCATTERING FUNCTIONS

The following graphs are taken from National Bureau of Standards Circular #542(24) and show the relation of energy and intensity of scatter as functions of the energy of the primary radiation and the scattering angle.

The Compton scattering by free electrons is described to a very good approximation by the Klein-Nishina formula. Experiment and theory have been found to agree within an experimental error of 1%.

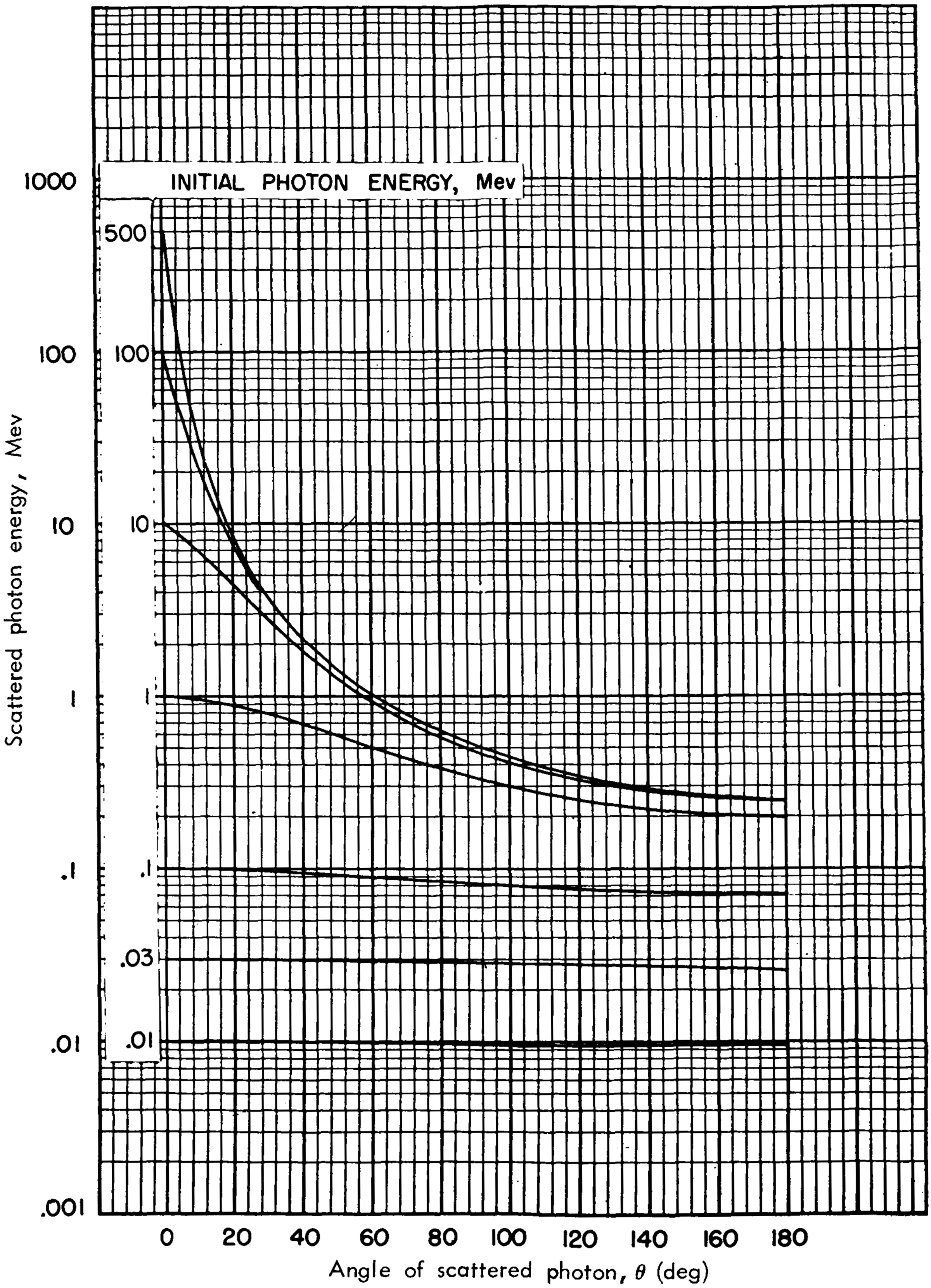

Fig. 10—Scattered photon energy versus angle in range of 0.01 to 500 MEV initial photon energy

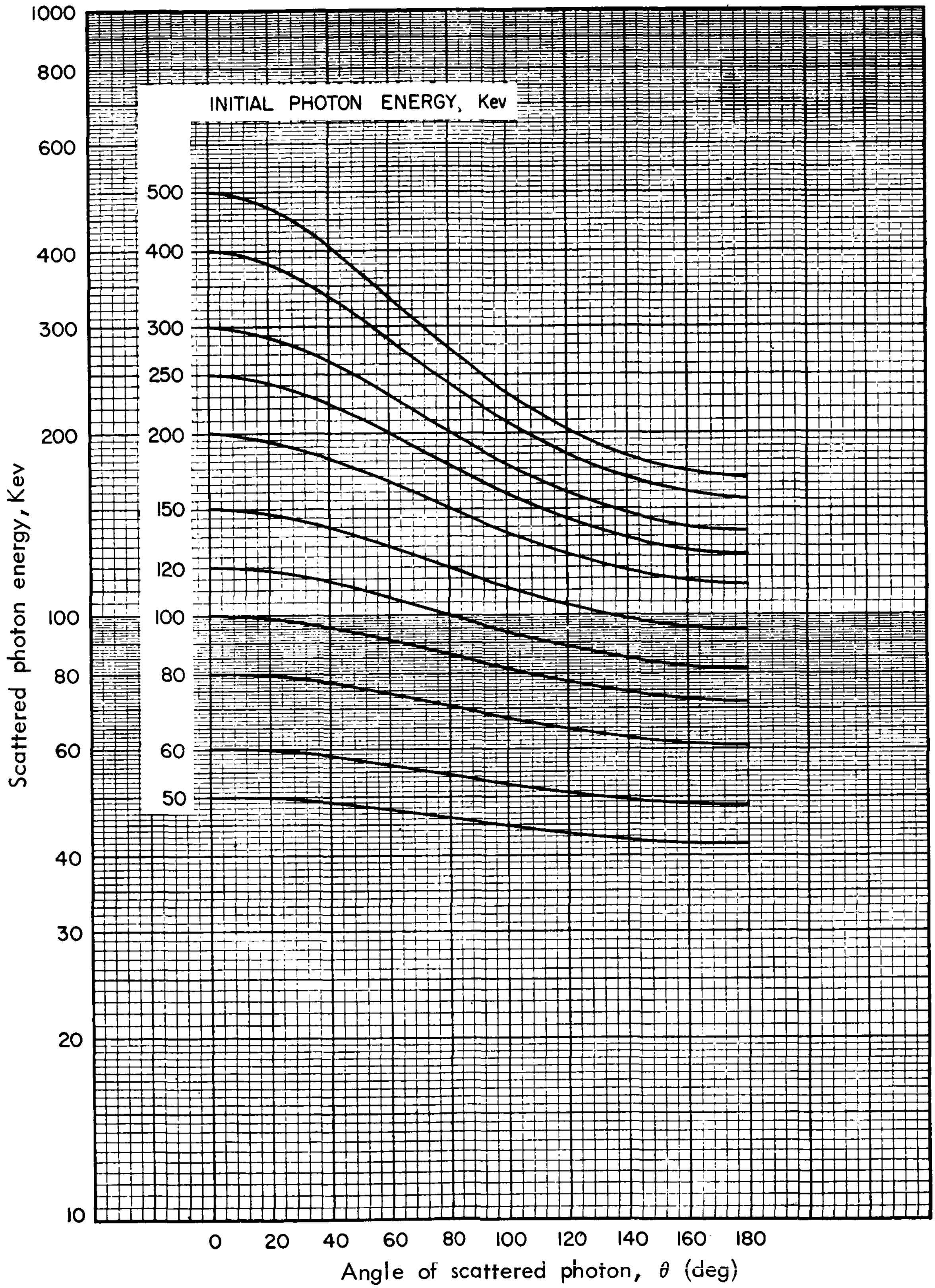

Fig. 11—Scattered photon energy versus angle in range of 50 to 500 KEV initial photon energy

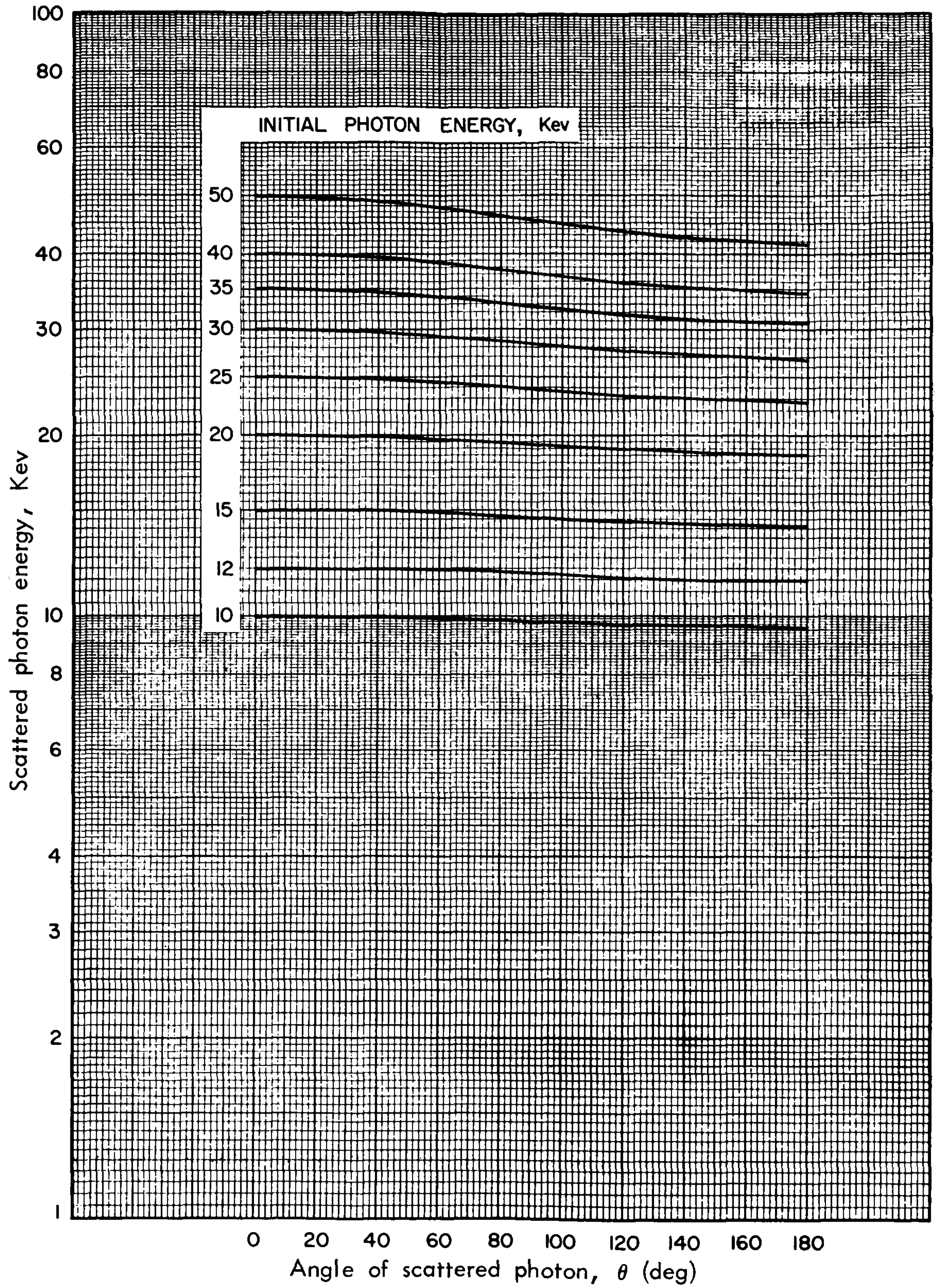

Fig. 12—Scattered photon energy versus angle in range of 10 to 50 KEV initial photon energy

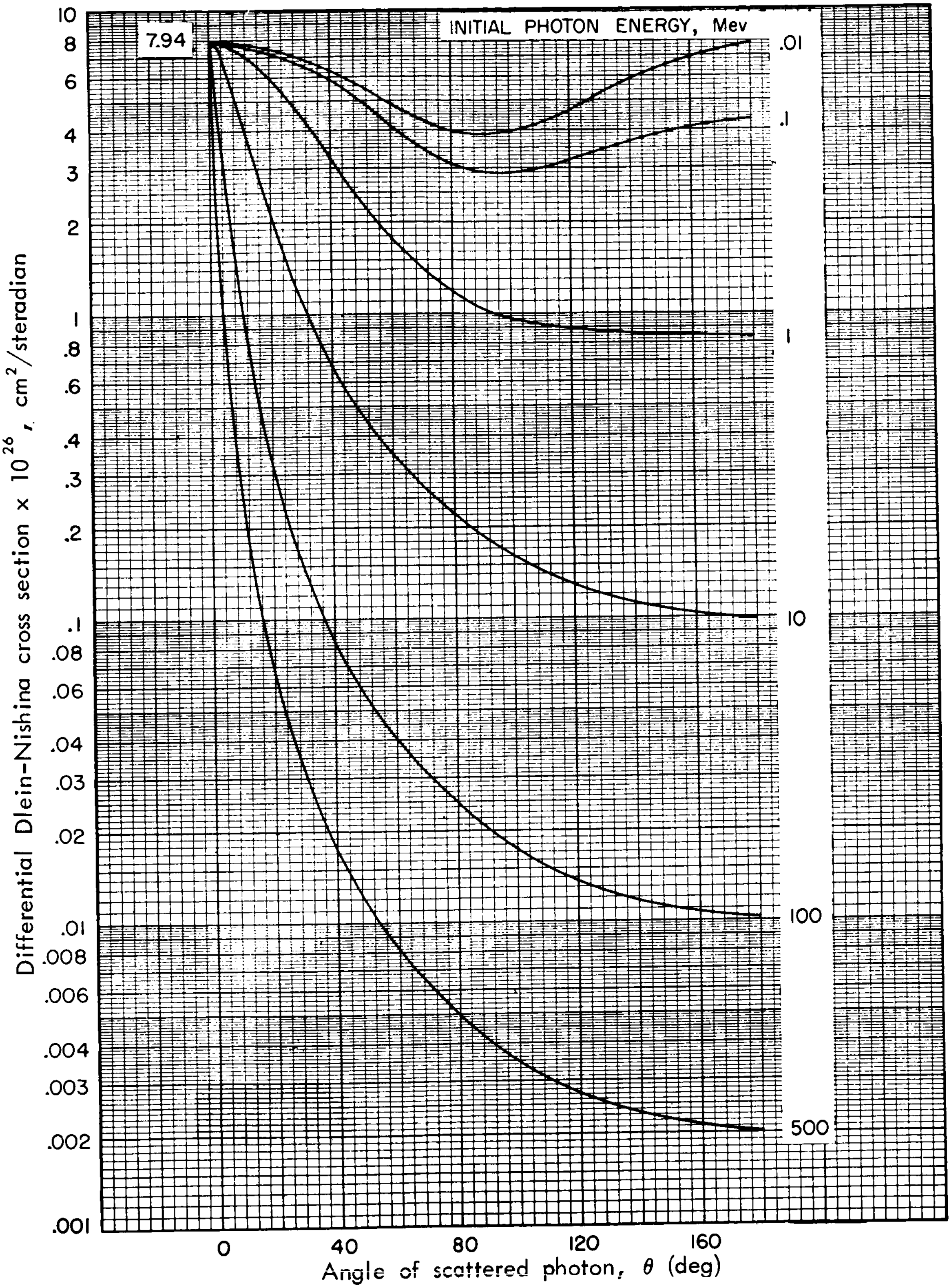

Fig. 13—Differential Klein-Nishina cross section per electron versus angle in range of 0.01 to 500 MEV initial photon energy

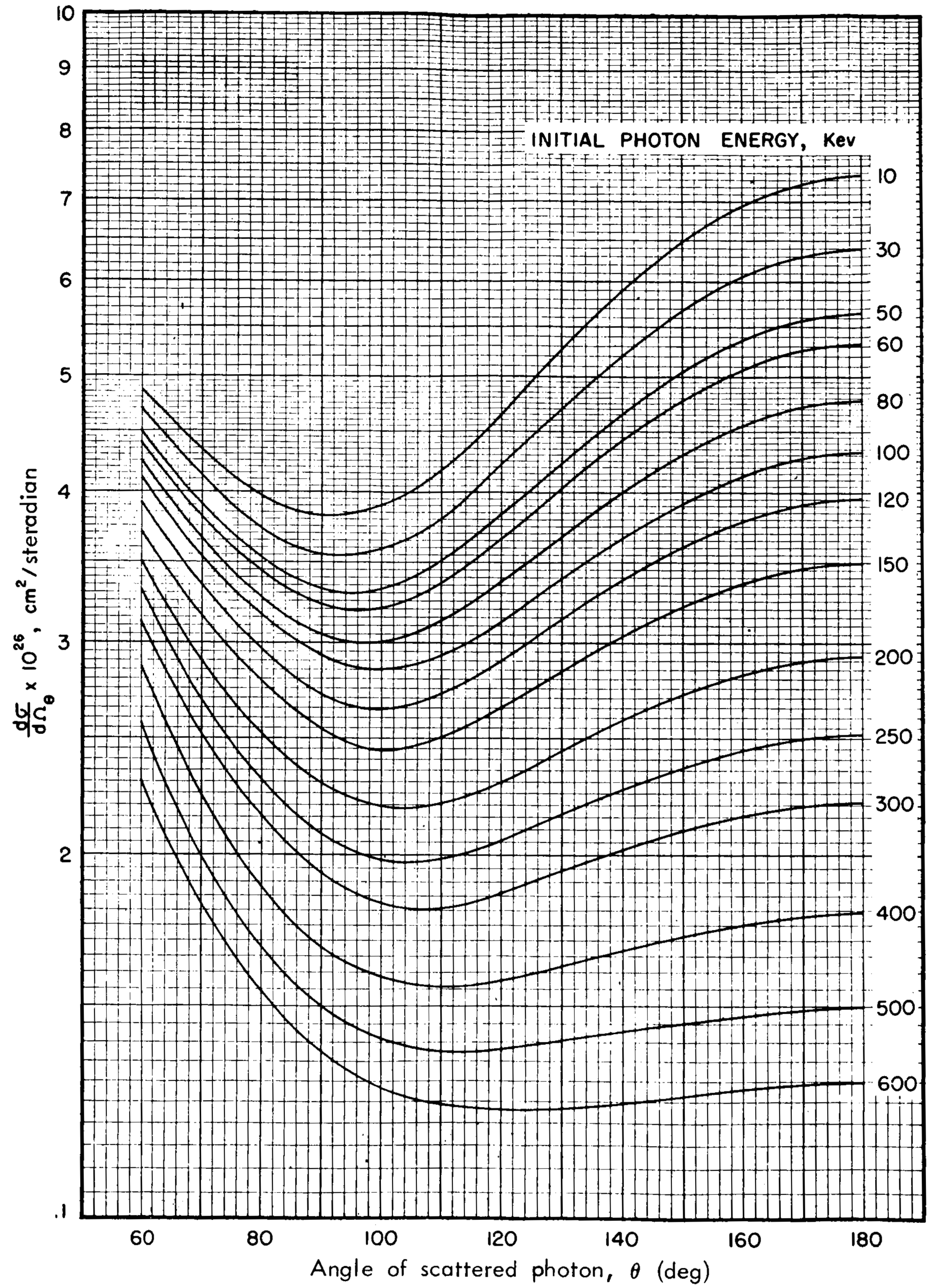

Fig. 14— Differential Klein-Nishina cross section per electron versus angle in range of 10 to 600 KEV initial photon energy

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