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ASD TECHNICAL REPORT 61-201

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EFFECTS OF OUTER-SPACE ENVIRONMENT IMPORTANT TO SIMULATION OF SPACE VEHICLES

EUGENE M. HART

CORNELL AERONAUTICAL LABORATORY, INC.
BUFFALO, NEW YORK

AUGUST 1961

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<p>ASD TR 61-201</p> <p>Aerospace Medical Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.</p> <p>EFFECTS OF OUTER-SPACE ENVIRONMENT IMPORTANT TO SIMULATION OF SPACE VEHICLES, by Eugene M. Hart. August 1961. 116 pp. incl. illus., tables, and 127 refs. (Proj. No. 6114; Task No. 60806) (Contract AF 33(616)-8858) Unclassified report</p> <p>The results of a literature survey undertaken to define the effects of the outer-space environment important to the simulation of space vehicles are presented. The discussion is general, having not been constrained by the inclusion of specific vehicles or trajectories.</p> <p>(over)</p>	<p>UNCLASSIFIED</p> <p>I. Hart, E. M.</p> <p>II. Aerospace Medical Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio</p> <p>III. Contr AF 33(616)-6858</p>	<p>ASD TR 61-201</p> <p>Aerospace Medical Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.</p> <p>EFFECTS OF OUTER-SPACE ENVIRONMENT IMPORTANT TO SIMULATION OF SPACE VEHICLES, by Eugene M. Hart. August 1961. 116 pp. incl. illus., tables, and 127 refs. (Proj. No. 6114; Task No. 60806) (Contract AF 33(616)-6858) Unclassified report</p> <p>The results of a literature survey undertaken to define the effect of the outer-space environment important to the simulation of space vehicles are presented. The discussion is general, having not been constrained by the inclusion of specific vehicles or trajectories.</p> <p>(over)</p>	<p>UNCLASSIFIED</p> <p>I. Hart, E. M.</p> <p>II. Aerospace Medical Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio</p> <p>III. Contr AF 33(616)-6858</p>
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**CORNELL AERONAUTICAL LABORATORY, INC.
BUFFALO, NEW YORK**

AUGUST 1961

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**BEHAVIORAL SCIENCES LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

FOREWORD

This report is the culmination of a study initiated by the Behavioral Sciences Laboratory, Aerospace Medical Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. The Project Officer was Mr. Arthur Sutton of the Simulator Research Section, Training Research Branch.

The study was performed by Cornell Aeronautical Laboratory, Inc., of Buffalo, New York, under Air Force Contract No. AF 33(616)-5858, Project No. 6114, "Effects of Outer-Space Environment Important to Simulation of Space Vehicles," and Task No. 60806, "Outer Space Environment, Simulation Study." The author, Mr. Eugene M. Hart of the Systems Research Department, was project engineer and performed the study under the direction of Mr. Sol Kaufman, Head, Electronics Systems Branch. The study was started 1 November 1959 and was completed 30 September 1960. This report was originally issued internally as CAL Report No. ST-1403-G-1.

Included among those at Cornell Aeronautical Laboratory who contributed to the study and preparation of this report were: Dr. David Kahn, Head, Systems Research Department; Mr. Robert Stevens, Assistant Head, Operations Research Department; Dr. William J. White, Head, Human Factors Section and Mr. Robert Duffy, Systems Research Department.

ABSTRACT

The results of a literature survey undertaken to define the effects of the outer-space environment important to the simulation of space vehicles are presented. The discussion is general, having not been constrained by the inclusion of specific vehicles or trajectories. Only the natural environment of space is considered and the survey is limited to the solar system with particular emphasis on the region in the near vicinity of the earth-moon system and at heights greater than 80 kilometers above the earth's surface. To specify those effects that need to be incorporated into a space training simulator, the exterior environment, its effects on the vehicle and crew, and the malfunctions that may result must be determined. These subjects are treated, along with a consideration of the adequacy of the existing data in the study. Recommendations for further study are presented.

PUBLICATION REVIEW

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INTRODUCTION

OBJECTIVE

This investigation was performed to determine what aspects of the natural environment of space must be simulated in training a crew for a space mission. To establish suitable ground-work for achieving this basic objective, a proportionately large effort was made in defining the environment (both spatial and temporal), its effects on the space vehicle and crew, and the malfunctions that may occur.

LIMITATION OF STUDY

The study has limitations. First, only the natural environment of space was considered and this was further limited to the solar system with particular emphasis on the region in the near vicinity of the earth-moon system at heights greater than 80 km above the earth's surface. Manned space missions presently foreseen in the near future will not be outside these limits.

Second, since only the natural environment was considered, not all of the conditions that may be experienced (and, therefore, require simulation) by a vehicle and its crew were accounted for. Outgassing, debris from previous probes, and, in time of war, hostile enemy action are but a few of the factors that may alter the natural environment in the vicinity of the vehicle.

Third, the study was general with no restrictions to specified vehicles or missions.

Finally, our knowledge of the space environment and the effects it will have on vehicle and crew was in many respects uncertain. The extent of this uncertainty reaches several orders of magnitude in some cases as our concept of the environment above satellite altitudes has been gained entirely by inference with the exception of measurements by a few deep space probes.

ASSUMPTIONS

It will be assumed that the simulator will reproduce the physical dimensions of the space cabin, its instrumentation, controls, etc. to the degree required for the simulation process to be meaningful. Therefore, the discussion is concerned only with the conditions created through the influence of the general space environment.

It is assumed further that the space vehicle to be simulated fulfills the following general design requirements:

1. The cabin is composed of a hermetically sealed, self-contained compartment with built-in, fail-safe precautions and provisions for repair or self-sealing of leaks,
2. The sealed cabin is a separate, integrated, self-sufficient unit isolated from the exterior walls. The outer structural wall should take the external loads and should act as a bumper against meteoritic penetration. The inner wall serves as a pressure vessel but is designed to take no other external loads,
3. The equipment and component systems are designed for ease of maintenance and, as far as possible, all repairs are done from inside the sealed cabin,
4. The environmental unit will simulate and automatically maintain moderate terrestrial conditions of atmospheric pressure up to 14.7 pounds per square inch (psi); oxygen concentration $25 \pm 5\%$ to maintain sea level oxygen pressure at cabin pressures from 14.7 to 8.3 psi (i.e., sea level to 15,000 ft.); nitrogen concentration, $75 \pm 5\%$; carbon dioxide concentration below 0.5%; carbon monoxide from all causes, maximum concentration 0.005%; temperature $70 \pm 10^\circ\text{F}$; and relative humidity depending on the temperature about $35 \pm 10\%$. Manual override controls are provided in case of automatic control equipment failure.
5. Other environmental factors to be included are:
 - a. illumination - 50 ft-candles; filter out all harmful ultraviolet
 - b. noise - 40 db normally
 - c. vibration - less than 0.0004 inch double amplitude between 100 and 500 cps and less than 0.00015 inch double amplitude above 1000 cps and below 60 cps.
6. The cabin will include facilities for feeding. Washing, sanitation, sleeping, and recreation facilities may be provided depending on the mission duration.
7. Special equipment or selected areas of the cabin are designed to protect the crew against the expected radiation environment to be encountered in space.

APPROACH

To determine the environmental aspects that require simulation, the following basic procedure was developed. First, the environment and the possible effects it may have on vehicle and crew were defined. To facilitate

the procedure a few general design requirements for the space vehicle were established. Next, the possible malfunctions that may result from the environment and its effects were listed. Taking into account these factors, plus the protection the space vehicle would provide and the present data on tolerances of the human to each aspect, conclusions were drawn regarding what environmental aspects require simulation.

All the environmental data presented does not contribute significant effects that must be simulated. This seemingly extraneous data was included because in many areas the data available at the present time contains a large degree of uncertainty. This applies not only to the environmental intensities in space but also to the intensities required to produce a significant effect. Consequently, because future data may be much different from that presently available it was desirous to briefly summarize as much data as possible to disclose the information on which all conclusions were based. Data available in the coming years through further research in the areas of uncertainty and in many new areas may show that many of the effects presently believed to be significant are not and vice versa, i. e., many effects presently overlooked should not have been.

ELECTROMAGNETIC RADIATION

The electromagnetic (EM) radiation sensed at the earth's surface is not at all representative of the radiation existing above the earth's atmosphere. Figure 1 discloses qualitatively the opaqueness of the earth's

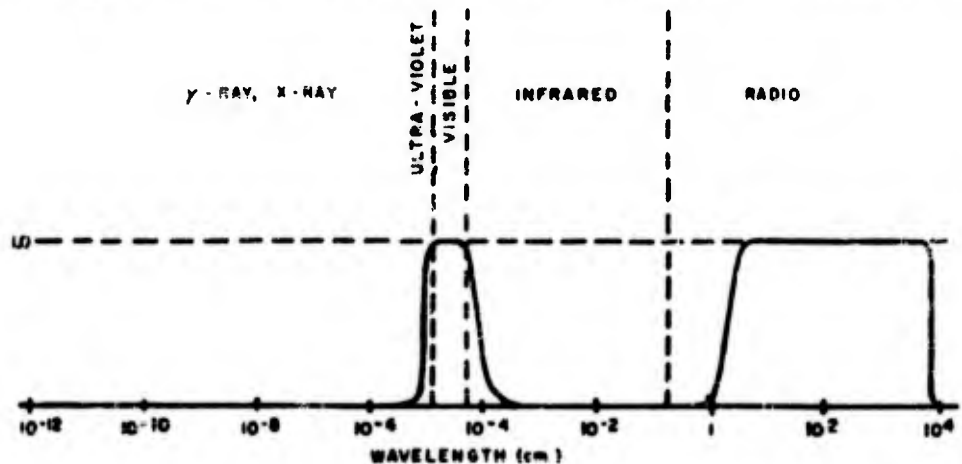


Figure 1. Schematic Transmission Coefficient of Earth's Atmosphere vs. Wavelength

atmosphere to EM radiation. The earth's atmosphere is impervious to EM radiation except for two relatively small portions of the entire wavelength spectrum (which nevertheless contains about 99% of the total EM flux present in space). A good deal is known about these two regions. Only recently have measurements been taken of the EM radiation by high-altitude and extra-atmosphere instrument carriers, and therefore far less is known about the other portions of the spectrum. These fragmentary measurements plus some theoretical considerations form the basis of our present knowledge of the EM radiation that exists in space.

The discussion of the electromagnetic environment, its effects on the space vehicle and its crew, the malfunctions that may result and, finally, those conditions requiring simulation are organized under the following sub-headings:

1. Radio Waves
2. Ultraviolet, Visible, Infrared and Soft X-rays
3. Hard X- and Gamma Rays

A short discussion of the adequacy of the existing data is included.

DESCRIPTIVE TERMS

The EM radiation received at a point in space can be described completely in terms of three qualities: spectrum, polarization, and magnitude, any of which may vary with time and direction.

The spectrum represents the distribution of radiation in frequency or wavelength. Spectra are usually classified as either line or continuous. Except for a few cases, such as the 1420 megacycles per second (mc/s) line emission from interstellar atomic hydrogen, extraterrestrial sources are generally continuous.

EM radiation is resolvable into two independent polarization modes (e.g., orthogonal plane polarizations or clockwise and counter-clockwise circular polarizations). However, most extraterrestrial sources are randomly polarized; therefore, unless otherwise noted, the decomposition into individual polarization modes will not be treated.

The magnitude of the radiation received at a point in space may be described in terms of brightness, flux density, or brightness temperature, sometimes denoted "equivalent black body temperature."

The strength of a source of EM radiation can be described by the spectral brightness (radiance), B_λ , in power per unit emitting area per unit solid angle per unit wavelength or B_f in power per unit area per unit solid angle per unit frequency, as a function of wavelength (or frequency) and emitter surface coordinates. In the absence of attenuation by an intervening medium (which is generally true in space) the received spectral brightness at any point can be calculated from the source spectral brightness.

It is often convenient to characterize a source by its brightness temperature. This is the temperature of a black body that would present the same spectral brightness as that of the observed object. For a black body the following expressions relate temperature and brightness:

$$B_\lambda = \frac{2hc^2}{\lambda^5(e^{hc/\lambda kT} - 1)} \quad B_f = \frac{2hf^3}{c^2(e^{hf/kT} - 1)} \quad (1)$$

where

h = Planck constant (6.26×10^{-27} erg-sec)

c = velocity of EM radiation in vacuo (3×10^{10} cm/sec)

k = Boltzmann's constant (1.38×10^{-16} erg/°K)

T = black body surface temperature (°K)

f = frequency, cps

λ = wavelength, cm

To fully describe a source in terms of the equivalent black body temperature requires the specification of the temperature as a function of wavelength (or frequency) and source coordinates. For the latter it is generally sufficient to work with relative angular coordinates, as for example the angular position along the solar disk radius.

Sources of minute angular dimensions are best described by the received spectral flux density, F_λ in power per unit area per unit wavelength or F_f in power per unit area per unit frequency.

RADIO WAVES* (0 to 3×10^{11} cps)

For a little more than two decades after Jansky's original discovery of cosmic radio noise in 1932, the practical implications of this phenomena were largely ignored. Now, however, improvements in communication systems have reached the point where extraterrestrial noise threatens to impose a fundamental limitation on man's ability to communicate over wide regions of the radio-frequency spectrum. This is particularly true when one considers the problems of communicating with a vehicle in space.

Within the discussion of the radio frequency environment in space an attempt is made to represent this environment by a few simple analytical expressions that are accurate to within an order of magnitude. The expressions presented are satisfactory except for a few specific cases noted within the discussion.

Environment

The sources which make significant contributions to the radio spectrum are:

1. Galactic emission**
2. Interstellar hydrogen gas
3. Discrete sources (radio stars)
4. Sun
5. Jupiter
6. Other planets in the solar system
7. Moon
8. Comets

* The expression "radio waves" includes those frequencies commonly designated "electric waves" (0 to 1×10^4 cps).

**This emission is associated with our galaxy, but its specific origin is not yet well established.

Practically all measurements have been in the wavelength region from 15 meters to 10 cm (2×10^7 to 3×10^9 cps) because of the severe limitations imposed by the earth's atmosphere and the inherent source intensities. Extrapolation beyond these limits has been attempted in a few cases.

For the radio frequency region and physically reasonable temperatures Planck's black body radiation law is well approximated by the simple expression:

$$B_f = \frac{2KTf^2}{c^2} = \frac{2KT}{\lambda^2} \quad (2)$$

Galactic Emission. Radio emission from the galaxy is the most widely dispersed of all the extraterrestrial radio sources. It appears to be present in all directions but is most intense near the plane of the galaxy and especially in the direction of the galactic center (in the constellation Sagittarius). Galactic noise has been mapped by various observers at frequencies between 20 and 3000 mc/s and a few measurements have been taken outside this range. Figure 2 presents a plot of antenna temperature,

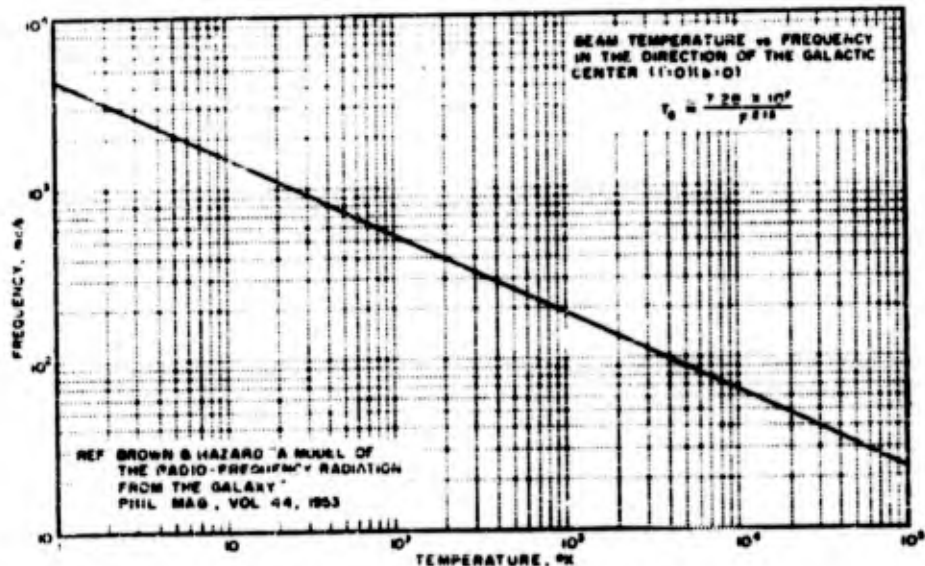


Figure 2. Galactic Radio Emission

for an infinitely directive antenna beam, versus frequency when pointed at the galactic center. This antenna temperature is equivalent to the previously described equivalent black body temperature. The curve in Figure 2 is approximated by the expression:

$$T_{G0} = (7.28 \times 10^7) f^{-2.13} \text{ } ^\circ\text{K} \quad (3)$$

where f is the frequency in mc/s and lies within the limits $15 \text{ mc/s} \leq f \leq 4000 \text{ mc/s}$ and T_{bg} = equivalent black body temperature measured in the direction of the galactic center.

Figures 3 and 4 exhibit some experimental data and approximate analytical fits thereto on the variation of intensity of galactic noise with angular departure from the galactic center.

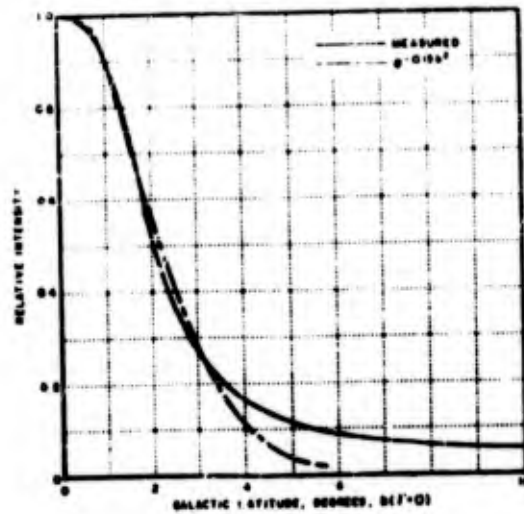


Figure 3. Variation of Intensity with Galactic Latitude at 480 mc/s

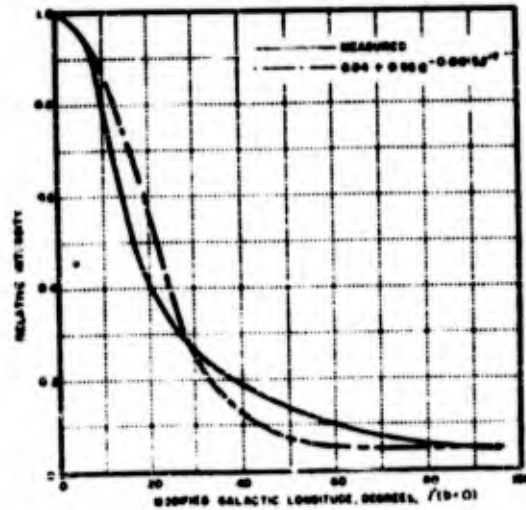


Figure 4. Variation of Intensity with Galactic Longitude at 480 mc/s

A simple analytic model for the galactic radio noise is:

$$T_G = 7.28 \times 10^{-5} [0.96 e^{-(0.0015l'^2 + 0.146l')} + 0.4] f^{-2.15} \quad (4)$$

where T_G = equivalent black body temperature, °K
 f = frequency, mc/s $15 \text{ mc/s} \leq f \leq 4000 \text{ mc/s}$
 b = galactic latitude, degrees
 l' = modified galactic longitude*, degrees

The above equation is accurate within an order of magnitude for all points on the celestial sphere except where certain localized peaks in radio emission occur. No provision is included for the dependence of received flux on receiver position because the distances to the source are large relative to the dimensions of the solar system. No time dependence is noted since all measurements thus far indicate the absence of measurable fluctuations.

Discrete Sources (Radio Stars). A large number of localized sources of relatively high brightness temperature exist and these have been designated "discrete sources" or "radio stars." The former term is the most proper as surveys taken in the last ten years show no connection between the localized radio sources and the visible stars. More than 3,000 discrete sources are presently known. Therefore their properties will be treated statistically but a few of the stronger sources will receive individual attention.

The appropriate quantity for representing the output of discrete sources is spectral flux density, specifically F_ν in watts/meter²/cps.

The distribution of discrete sources in galactic latitude discloses that sources of small angular diameter (< 20 minutes) are distributed very uniformly over the sky. These are usually designated Class II sources. On the other hand, discrete sources of large angular diameter (> 20 minutes), Class I sources, have a marked concentration in the galactic plane, see Figure 5. Class I sources are probably members of the galaxy while those of Class II, on the basis of their angular distribution alone, cannot be definitely classified as galactic or extragalactic.

* Modified galactic longitude is merely a translation of normal galactic longitude i.e., $l = l' + 327^\circ$, to place the ordinate at the galactic center.

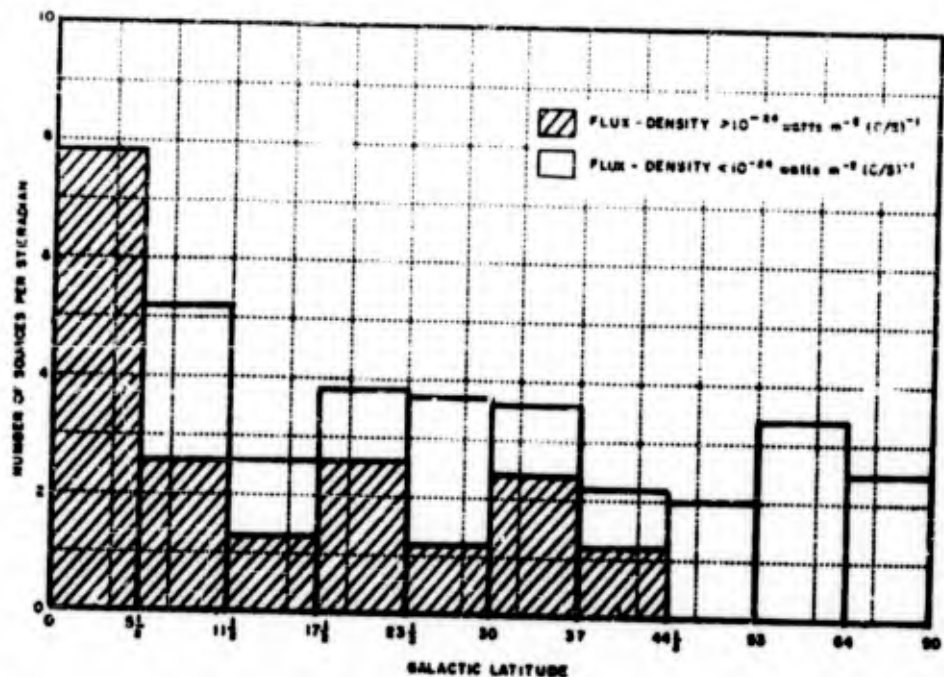


Figure 5. Distribution in Galactic Latitude of Sources of Large Angular Diameter (>20') Class I

The spectral flux density versus frequency for the frequency interval from 20 to 1000 mc/s is shown in Figure 6 for four of the more intense discrete sources thus far discovered: Cygnus A, Virgo A, Centaurus A and Taurus A. The slope of the curve for Taurus A is much different than the slope of the other three sources, and differs from those of most discrete sources. For those discrete sources whose spectral flux density versus frequency has been measured, all exhibit the characteristic of a declining flux density with increasing frequency (in contrast to the ideal black body which has a slope of opposite sign in the radio frequency spectrum. Nevertheless, the spectral flux density for all four sources can be approximated very closely by:

$$F_F = C_1 + C_2 f^{-\alpha} \quad 20 \leq F \leq 1,000 \text{ mc/s} \quad (5)$$

where F_F = spectral flux density, watts m⁻² cps⁻¹

f = frequency, mc/s

C_1, C_2, α = constant coefficients

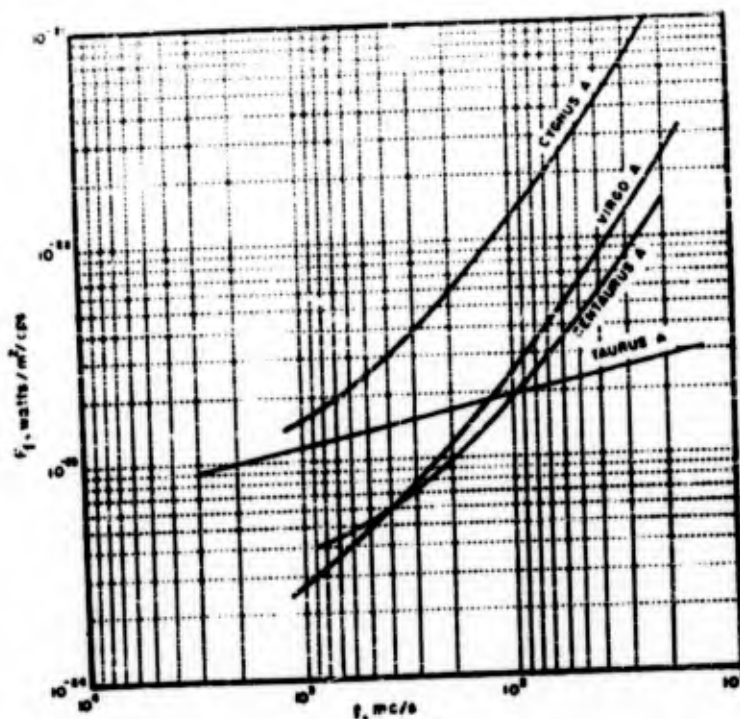


Figure 6. Spectral Flux Density of Four Intense Discrete Radio Sources

The appropriate values for the coefficients are:

	C_1	C_2	α
Cygnus A	1×10^{-23}	8×10^{-20}	-1.4
Virgo A	2×10^{-24}	1.6×10^{-20}	-1.4
Centaurus A	3×10^{-24}	1.0×10^{-20}	-1.4
Taurus A	9.8×10^{-25}	6.1×10^{-23}	-0.25

As in galactic noise there is no evidence for temporal fluctuations of the emission of radio stars.

Data for some reliably known discrete sources are presented in Table I.

Table 1
Some Reliably Known Discrete Sources

Name	IAU No.	Position (1950)		Spectral Flux Density $\times 10^{-24}$ watts m^{-2} cps $^{-1}$ 100mc/s 1420mc/s		Angular Diameter* minutes of arc	Identification
		RA	Dec				
Cassiopeia A	21N5A	23 ^h 21 ^m	58°32'N	200	27	5.5	Peculiar galactic nebulosity
Sagittarius A	17S2A	17 ^h 42 ^m	29°01'S		17		
Cygnus A	19N4A	19 ^h 58 ^m	40°36'N	125	15	1.1	Two spiral galaxies in collision
Puppis A	08S4A	08 ^h 20 ^m	42°48'S	35			Peculiar galactic nebulosity
Taurus A	05N2A	05 ^h 31 ^m	21°59'N	19	11	4	Crab Nebula M1
Centaurus A	13S4A	13 ^h 22 ^m	42°46'S	24	3	6	Peculiar galaxy NGC 5128
Virgo A	12N1A	12 ^h 28 ^m	12°40'N	12	3	5	Peculiar galaxy M87, NGC 4486
Andromeda	00N4A	00 ^h 40 ^m	41°00'N	2	~.2		Andromeda Nebula M31, NGC 224
Perseus	03N4A	03 ^h 16 ^m	41°19'N	1			Peculiar galaxy NGC 1275

* based on the effective extent of the sources between points where the surface brightness decreases by a factor of two.

Monochromatic Galactic Radio Waves. So far cosmic radio waves whose emission spectra are essentially continuous have been discussed. In 1944, van de Hulst presented a paper in which he showed that transitions between the hyperfine levels of the ground state 1^2S of the hydrogen atom produce a line of wavelength about 21cm. The line was first observed in 1951 by Purcell.

The 21 cm (1420 mc/s) radiation is concentrated in a band that roughly follows the Milky Way (Reference B15). Such a distribution confirms optical information about the concentration of interstellar hydrogen in this zone. The maximum brightness temperature is near 100°K.

Hydrogen - the most abundant element in the universe - produces only one observable radio line ($\lambda = 21$ cm). We may expect a weak line of deuterium ($\lambda = 91.6$ cm) and possibly some very weak molecular lines but these will be insignificant relative to the above.

The Sun and Other Solar System Sources. The sun is the most intense source of radio emission that contributes to the space environment in the near vicinity of the earth-moon system. The radiation consists of a temporally invariant component, plus a fluctuating component, the latter often correlated with sunspots, solar flares, and other visual phenomena. The invariant component, observed alone under quiescent

conditions, is completely described by a spectral brightness function of wavelength and angular position, along a solar radius. It is often convenient to speak of the sun's average spectral brightness; this is computed as the quotient of solar spectral flux density divided by the visible disk solid angle. Associated with the average spectral brightness is an average equivalent black body temperature, T_{λ} , and this quantity is plotted versus wavelength in Figure 7. An expression that fits the curve extremely well is

$$T_{\lambda} = 10^4 \lambda^{-1} \text{ } ^\circ\text{K} \quad 1 \text{ cm.} \leq \lambda \leq 1,000 \text{ cm.} \quad (6)$$

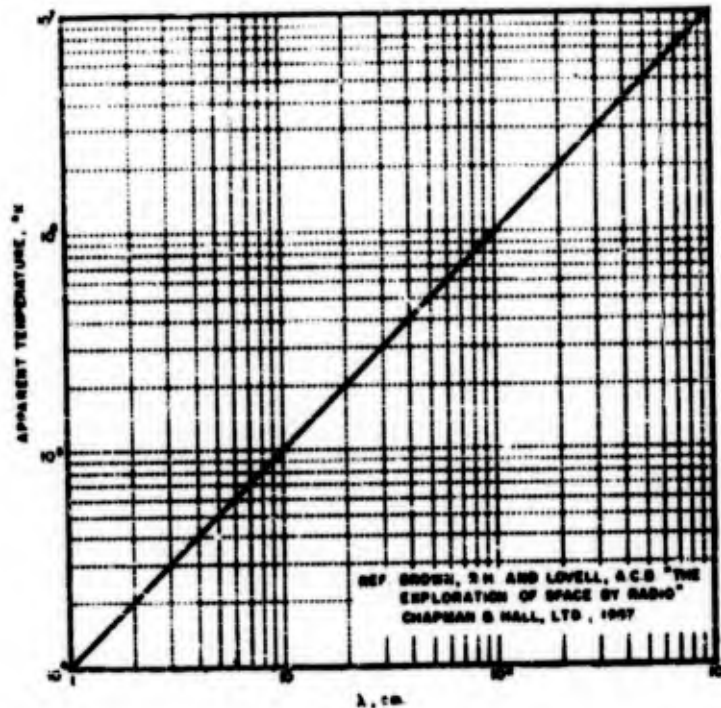


Figure 7. Variation of the Apparent Black Body Temperature of the "Quiet" Sun with Wavelength

If one computes the total solar flux density from Equation 6 in the radio spectrum it is found to be of the order of 10^{-12} watt/cm² as compared with $\sim 10^{-1}$ watt/cm² in the visible region.

An expression which approximates the spectral brightness in terms of an associated black body temperature as a function of wavelength and position on the solar disk is:

$$T_{bs} \approx (10^4 - 380\lambda^{1/2})\lambda \left[\frac{1}{\frac{R_o - 1}{e^{0.00065\lambda + 0.061} + 1}} \right] ^{\circ}K \quad (7)$$

where

T_{bs} = brightness temperature across solar disk, $^{\circ}K$

R_o = ratio of the distance from the center of the solar optical disk to the radius of the optical disk

λ = wavelength, cm

Figure 8 is a plot of the measured brightness temperature versus position on the solar disk for two wavelengths. The analytical expression given by Equation 7 was derived to fit within less than one order of magnitude the measured curves shown in Figure 8.

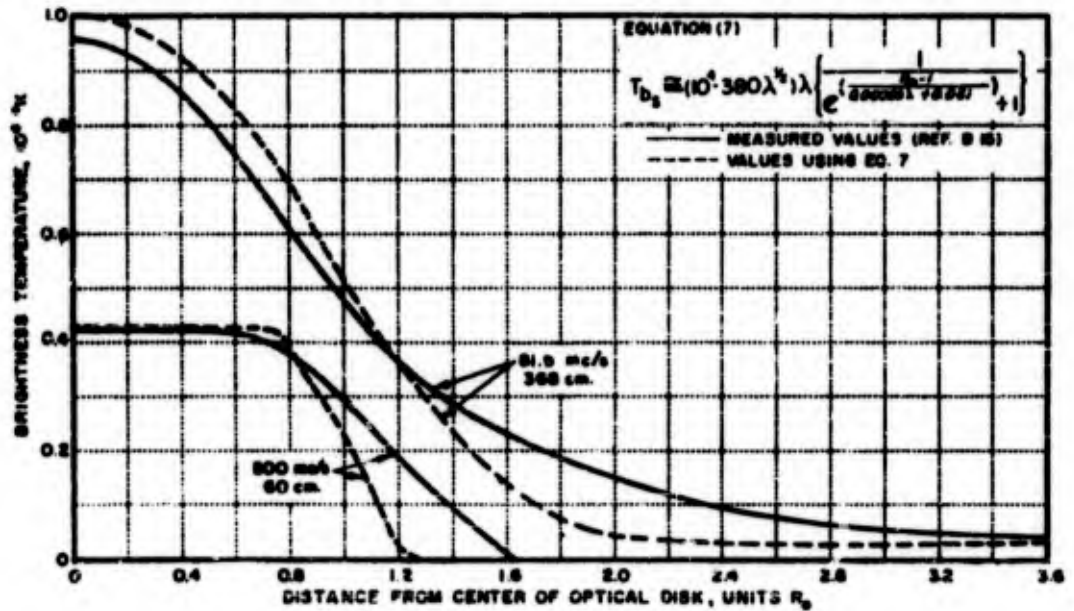


Figure 8. Observed Brightness Distribution Across the Sun

To account for the fluctuating component of solar radio emission it appears adequate to modify the average disk temperature, T_{a_3} . A reasonable procedure is to introduce a variable factor, $A(\lambda)$, into Equation 6, therefore

$$T_{a_3} = 10^4 \lambda A(\lambda) \quad (8)$$

where A is a stochastic quantity dependent on λ and $A(\lambda) \geq 1$. Several components of A may be distinguished, including a slowly varying sunspot-number-dependent factor (maximum value rarely reaches $A(\lambda) = 2$) and short term outbursts, noise storms and isolated bursts for which augmentations up to 10,000 have been recorded. The numbers just quoted apply to the meter wavelength region; in the microwave regions, variations by more than a factor of two or three are quite rare.

The location of the observer does not influence the solar temperatures as discussed, because these are inherent properties of the source. The apparent (visible) disk size Ω changes according to the relation:

$$\Omega = \frac{\Omega_s}{R^2} = \frac{6.8 \times 10^{-5}}{R^2} \text{ sterad} \quad (9)$$

where

R = distance observer is from the sun in astronomical units

Ω_s = visible disk size at one AU from sun

and this causes the flux density to vary as the inverse square of distance from the sun.

The solar system contains additional radio emission sources. A few of these are: Jupiter (with outbursts lasting from a few seconds to hours at frequencies up to 18 mc/s; peak spectral flux density recorded is 10^{-19} watt m^{-2} cps $^{-1}$), Saturn and Venus (only uncorroborated reports of reception in the vicinity of 20 mc/s; peak spectral flux densities 6×10^{-21} and 10^{-21} watt m^{-2} cps respectively), Comet: Arend-Roland (8×10^{-23} watt m^{-2} cps at 600 mc/s and a distance of 7 AU), and thermal radiation from nearby planets and their satellites (Reference B18).

Effects

The radio waves that exist in space are of such low intensity that until the past few years they were of concern only to those interested in radio astronomy. Recent improvements in communication systems have made these waves significant because of the noise they introduce into communication systems. Other than noise, no detrimental effect is foreseen unless a localized radio source is approached; this will not be done in the near future.

Communication Noise. Figure 9 presents a block diagram for the chief sources of noise in a terrestrial communication system; for a space-to-space system only the atmospheric noise will be absent. The total input tending to distort the desired signal, and in many cases imposing a serious limitation on the ability to communicate over wide ranges of the radio frequency spectrum, is composed of a number of separate noise inputs.

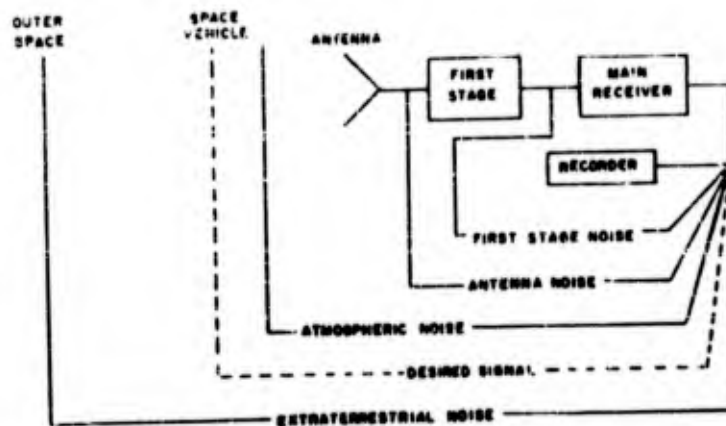


Figure 9. Chief Sources of Noise for a Terrestrial Receiver

Among the extraterrestrial noise sources, galactic noise is the most widely distributed and, except for communications taking place within a small angular subtense from a localized emitter, must be considered the most significant. Although the sun is the strongest radio emitter, within the solar system, it is considered to be less important than galactic emission because it subtends only a small portion of the surroundings and usually can be avoided.

The noise power received by a directional receiving system from a radio source is inversely proportional to the square of the distance between the receiving system and the source, thus

$$P_R = P_e \left(\frac{r}{R} \right)^2 A \quad (10)$$

where

P_R = noise power received by a receiving system, watts/cps

P_e = noise power density received at some reference point, watts/meter² cps

r = distance between the source and the reference point

R = distance between the source and the receiving system, in units of r

A = effective antenna aperture, meter²

The above expression is true for localized radio emitters in the main beam of the antenna. For sources outside the main beam, the side lobe effects will reduce the received power, depending on the antenna design, a representative figure for the sun being a decrease of 20 db.

Solar and galactic noise are the predominant noise sources for a communication system located in the near vicinity of the earth-moon system. Galactic noise although less intense will be the most important because solar noise occupies only a very small portion of the surroundings. Figure 10 shows the noise received by a communication system at a distance of one astronomical unit (1 AU) from the sun in terms of the noise temperature $^{\circ}\text{K}$.^{*} For comparison, plots of the internal noise of three typical low noise receiver designs are included.

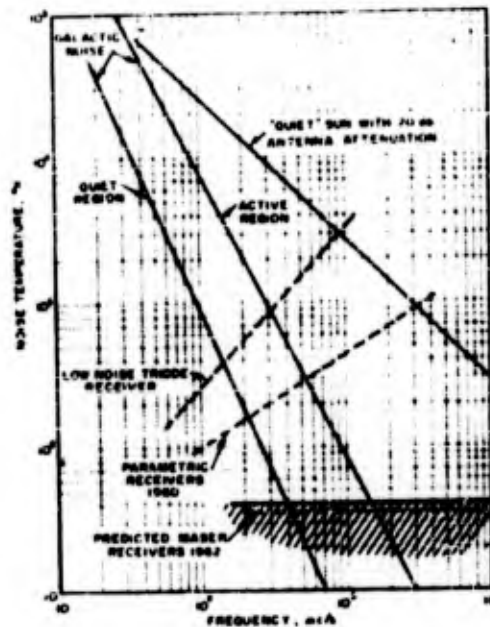


Figure 10. Frequency Dependence of Noise Sources One Astronomical Unit from the Sun

The internal noise level in present-day receivers over much of the radio frequency spectrum is greater than galactic noise. If future maser receivers perform as well as predicted, then galactic noise sets a definite lower limit to which a receiving system can be designed, consequently limiting the spatial distances over which communication can take place. On this basis a low-noise, high-frequency (e.g., microwave) communication system is best for long-distance space communication because of the decrease in galactic noise with frequency.

^{*}Noise temperature is the temperature of a black-body surface which would give the received noise power observed when placed in the antenna beam, neglecting other noise sources such as the receiver, antenna transmission line, etc.

Aspects Requiring Simulation

The EM radiation in the radio wave region results in a noise input to the communication system. Consequently, during portions of a space vehicle's trajectory this noise (depending on the type of communication system used, the direction in which the antenna is directed, solar activity, etc.) may interfere with communications and at times make the received signal completely unintelligible. This interference with communications should be simulated.

INFRARED ($8000-10^6 \text{ \AA}$) VISIBLE ($4000-8000 \text{ \AA}$), ULTRAVIOLET AND
SOFT-X-RAY ($3-4000 \text{ \AA}$)

Approximately 99% of the EM energy received by a space vehicle in the near vicinity of the earth-moon system will be in the infrared through soft X-ray portion of the spectrum. Therefore, this portion of the spectrum is expected to present problems more significant than those associated with the other two regions.

Environment

Within the spectral region from infrared (IR) to soft X-ray the main sources which contribute significantly to the environment of the earth-moon system, in order of decreasing intensity, are:

- . Sun
- . Earth-reflected sunlight and earth thermal radiation
- . Moon-reflected sunlight and thermal radiation
- . Stars, planets and other celestial bodies
- . Zodiacal light and earth air-glow

The sun, and to a lesser extent the reflected sunlight and thermal radiation from the earth and moon, depending on the receiver's position in space, are the only significant contributors of radiation in the above spectral region. Starlight (including the reflected light from the other planets), zodiacal light (solar radiation scattered by interplanetary matter) and earth air-glow (line emission from the recombination of atmospheric ions) are very weak compared to the others.

Sun. Except for sporadic soft X-radiation which will be discussed later, the sun's emission in the $3000 \text{ \AA} - 10,000 \text{ \AA}$ region is fairly uniform both in time and in distribution over the solar disk. (The total variation in solar energy output in this region being less than 1/2 of one percent.) Therefore a single equivalent black body temperature as a function of wavelength will represent the output adequately, see Figure 11. The curve has been extended to the radio frequency region to provide a more comprehensive picture of total solar electromagnetic output. An analytical fit in the region $\text{\AA} < \lambda < 10,000 \text{ \AA}$ is:

$$T_s = 9200 \lambda^{0.05} \quad ^\circ K \quad (11)$$

where λ is in cm.

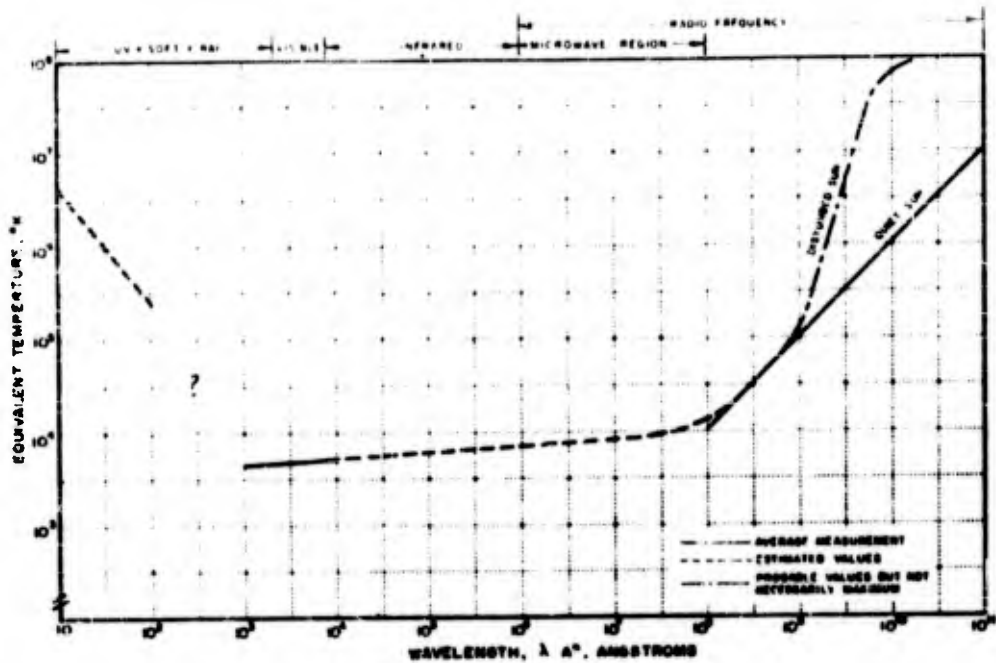


Figure 11. Approximate Equivalent Temperature vs. Wavelength

The received spectral flux density at any location is then given by:

$$F_{\lambda_s} = \frac{2c^2}{\lambda^5 (e^{\lambda K T_s(\lambda)} - 1)} \frac{\Omega_s}{R_s^2} \quad (12)$$

where

F_{λ_s} = energy flux per unit area per unit wavelength,
watts cm^{-2} unit wavelength $^{-1}$

K = Boltzmann's constant

$T_s(\lambda) = 9200 \lambda^{0.05}$

Ω_s = solar disk solid angle to an observer at 1 AU from the sun

R_s = distance from sun to the receiver, AU

Figure 12, another representation of the data in Figure 11, presents the energy fluxes involved from soft X-rays through a portion of the radio spectrum. High and low points in the radio range refer to conditions at sunspot maxima and minima respectively. The emission of the Lyman α and Lyman β lines of hydrogen is indicated in the ultraviolet near 10^3 \AA . The dotted curves indicate approximately the increases in solar radiation possible during periods of intense solar flares. Since the flux has been plotted at each point for a bandwidth equal to one wavelength this, when taken with a logarithmic scale of wavelength, gives a plot which is linear in regard to energy along the horizontal axis. The flux integrated over all wavelengths is $1.38 \times 10^3 \text{ watts m}^{-2}$.

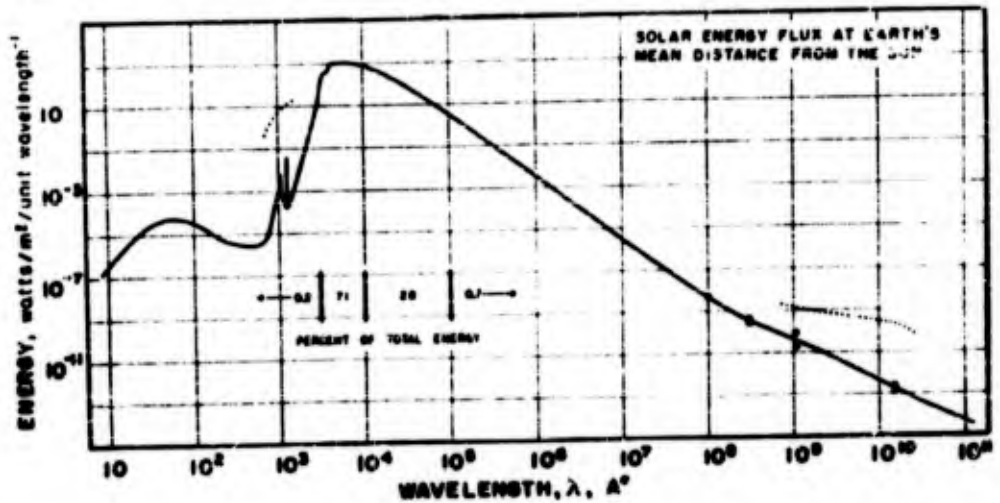


Figure 12. Solar Energy Flux at Earth's Mean Distance from the Sun

Soft X-rays are also present in solar radiation. Rocket data have indicated the intensity for a quiescent sun to be near $0.003 \text{ erg/cm}^2\text{-sec}$ in the $8\text{-}12 \text{ \AA}$ (Reference A19).

Earth and Moon. The earth's electromagnetic output may be represented as the sum of a reflected sunlight component and a thermal radiation component. The spectral composition of the former would be that of the sun modified by a reflection factor (albedo) which is generally a function of wavelength. Little is known about the value of the earth's albedo either as a detailed function of wavelength or beyond the visible and infrared spectrum. The average visual albedo is about 0.4. Hence as a first approximation

$$F_{\lambda e_1} = 0.4 F_{\lambda s} \left(\frac{R_0}{R_e} \right)^2 f \quad (13)$$

or

$$F_{\lambda e_1} = 0.4 \frac{2C^2 \Omega_s}{\lambda^5 (e^{hc/\lambda k T_s(\lambda)} - 1)} \cdot \left(\frac{R_0}{R_e} \right)^2 f \quad (14)$$

where R_0 is the earth's radius, R_e is the distance of the observer to the earth's center and f is a form factor, varying from 0 to 1, which depends upon R_e and the sunlit percentage of visible earth's surface.

To provide a reasonable approximation to the thermal radiation component, one can assume that the earth is a black body at a uniform surface temperature,

$$T_e = \begin{cases} 287^\circ\text{K in sunlight and} \\ 277^\circ\text{K in the shadow portion, then} \end{cases}$$

$$F_{\lambda_{e_s}} = \frac{2c^2}{\lambda^5 (e^{hc/\lambda K T_e} - 1)} \cdot \frac{\pi R_0^2}{R_e^2} \quad (15)$$

With respect to integrated power density, $F_{\lambda_{e_s}}$ contributes approximately 0.06 watt/cm² in the near vicinity of the earth's surface.

Analogous expressions apply to the moon. Here the albedo is better known; the average value over the visible spectrum is 0.07. Allowance should be made for the fact that lunar surface temperature is significantly different over night and day hemispheres. Representative value would be $T_{m_d} = 400^\circ\text{K}$, $T_{m_n} = 120^\circ\text{K}$.

Effects

The electromagnetic radiation present in space for the wavelength region extending from infrared through soft X-rays has been relatively well known for years but only recently has its effects on materials been considered. Except for surface heating, little is known about the magnitude and significance of their possible effects.

Surface Heating. The heat input to a vehicle in space is determined by the intensity and spectral distribution of the thermal radiation incident upon its surface and the absorptency of the surface for such radiation. For a vehicle operating within the solar system, such radiation is predominantly solar radiation, although for earth satellites the reflected and emitted radiation from the earth must also be considered. The heat dissipation likewise occurs by radiation and the temperature at which the rate of radiation equals the rate of absorption is dependent upon the total power emitted by the vehicle.

Controlling the temperature of a space vehicle is, in principle, a very simple problem. The body is not in contact with an atmosphere of any appreciable density, so there is no heat transfer by conduction or convection. It has been demonstrated theoretically that almost any practical temperature can be achieved and held at an almost constant value without recourse to refrigerating or heating devices by using simple mechanisms to adjust a system of reflecting or absorbing screens on the outer surface.

Deterioration of Organic Coatings. For many years ultraviolet radiation has been known to cause severe deterioration of organic coatings. Initial studies (see, for example, Reference A9) have indicated that, at least for polymers, in most cases the deterioration is less rapid in a vacuum than in air. No meaningful data on the exposure time required to produce substantial degradation are presently available.

Protective coatings have been developed. However, their usefulness over extended time periods, i.e., years, is in doubt.

Photoelectric Emission. The extreme ultraviolet (EUV) and soft X-ray spectrum can produce photoelectric emissions not only by metals but also by non-metals. The effects resulting from and the extent of damage due to this phenomenon have not been studied sufficiently by various investigators to permit numerical data to be released, but preliminary results have indicated that the optical properties* (or properties of optical mechanisms, e.g., lenses) of a vehicle may be altered significantly in a few years time.

Tissue Damage. Ultraviolet and soft X-rays are known to cause erythema, but both of these are easily attenuated by small thicknesses of structural materials. Present data (up to 1960) indicates the solar radiations in the ultraviolet and soft X-ray regions do not constitute a direct hazard to space vehicle crews. The wall thicknesses required for a pressurized hull should provide adequate protection from any radiation in this region detected thus far.

Illumination. The extra-atmospheric illumination is about 13,500 ft-candles compared with 10,000 ft-candles at the earth's surface on a bright day. The extra-atmospheric sky luminance is 10^{-5} millilambert (mL) compared to 500 mL in the lower atmosphere (Reference B19). Therefore because of the high contrast between the sun or any other sun-lit object, and the background of space it will be necessary to use a glass of very high absorptive power in all observation ports.

Radiation Pressures. The pressure of solar EM radiation has been neglected in many studies. The effect of radiation pressure in accelerating a vehicle is quite minor, but the total pressure on a vehicle can be of the order of one dyne. Therefore, if the center of pressure of the radiation were as much as one centimeter from the center of gravity the effect could, depending on the vehicle's moment of inertia, turn the vehicle through 360 degrees in a few hours.

Torques resulting from internal equipment, misalignment of propulsion motors and even from condensed matter striking the vehicle may far outweigh solar torque.

*The surface optical properties are the emissivity and absorptivity characteristics of a surface for ultraviolet, visible and infrared wavelengths.

Primary Malfunctions

The only significant problem presently foreseen as resulting from electromagnetic radiation within the infrared through soft X-ray portion of the EM spectrum is surface heating of the vehicle. Consequently an intolerable temperature limit is the only primary malfunction that may occur within the vehicle for either or both equipment and crew.

The internal temperature of a space vehicle, in principle, can be accurately controlled by either a passive or active system. The passive system would consist of adjustable absorbing and reflecting screens on the vehicle's exterior surface, programmed to keep the internal temperature at an almost constant value, within the limits of the crew or equipment. The active system depends on heating or refrigerating devices to control the internal temperature.

Both temperature control systems depend on the ability of the vehicle's exterior surface to absorb or radiate heat. Consequently, any change in the surface optical properties will change the load placed on the system. Therefore, if the optical properties are altered sufficiently the system might be unable to carry the additional load resulting in intolerable temperatures for either crew or equipment. As will be seen in a later section, the optical properties of a vehicle's surface will be altered by a combination of meteoritic erosion, photoelectric emission, ion sputtering and others in about one year.

Aspects Requiring Simulation

At the present time the only condition resulting from the infrared through soft X-ray portion of the EM spectrum that requires simulation is the space cabin temperature time-history. The temperature and humidity conditions in which the crew and equipment must operate will affect their performance. Therefore, the simulation should include the expected temperature time-history of the cabin and also, if it is expected that these temperatures will affect equipment, the effects should be simulated.

HARD X- AND GAMMA RAYS ($< 3 \text{ \AA}$)

The few attempts made at detecting any hard X-rays or gamma rays in space have proved to be futile. Future satellites enabling the regions of space to be explored for relatively long durations of time with very sensitive equipment may discover hard X- and gamma rays in the natural environment of space, but at the time of this writing, their existence in measurable quantities is very much in doubt.

If hard X-rays and gamma rays do exist in space, they will affect the space vehicle and its crew. However, discussion of the effects is not possible unless the intensities are known, because to list all effects that may result is not reasonable. Therefore, at the present time no conclusions will be drawn.

ADEQUACY OF EXISTING DATA

The earth's atmosphere is transparent for two wavelength regions in the electromagnetic spectrum, Figure 1, and within these two regions, the data on the environment in space are relatively complete. Any additional data within these regions would only refine that already available and consequently contribute no new problems.

Outside these two regions, there are areas wherein no data or only a very limited amount exists. These include:

1. accurate measurements of the earth's albedo,
2. the existence or nonexistence of hard X-rays and/or gamma rays and if they exist their intensity, and
3. further data on the spectral intensity of soft X-rays.

Data on the magnitude of the effects caused by the EM spectrum is scarce in many areas. These include:

1. the effects of ultraviolet radiation on organic and inorganic coatings over relatively long periods of time,
2. the significance of photo-electric emission of metals and non-metals due to EUV and soft X-rays.

CORPUSCULAR RADIATION

Corpuscular radiation as it exists in space can be divided into three categories. The first is composed of those energetic particles that comprise the radiation belts surrounding the earth, designated semipermanently trapped radiation. The second is composed of those particle streams that, upon striking the earth's atmosphere, produce the visual phenomenon known as aurorae, designated low altitude radiations. The third is composed of those particles that make up cosmic rays characterized as galactic and solar cosmic rays.

SEMI-PERMANENTLY TRAPPED RADIATION

A region of intense radiation was initially discovered by Explorer I (1958 α). This region designated "The Great Radiation Belt" or "Van Allen Belt" exists at latitudes less than 70° and altitudes extending from about 600 miles to approximately 30,000 miles. The belt is divided into two zones, designated simply as the inner and outer zones, with a region between the two usually called the "slot" (see Figure 13).

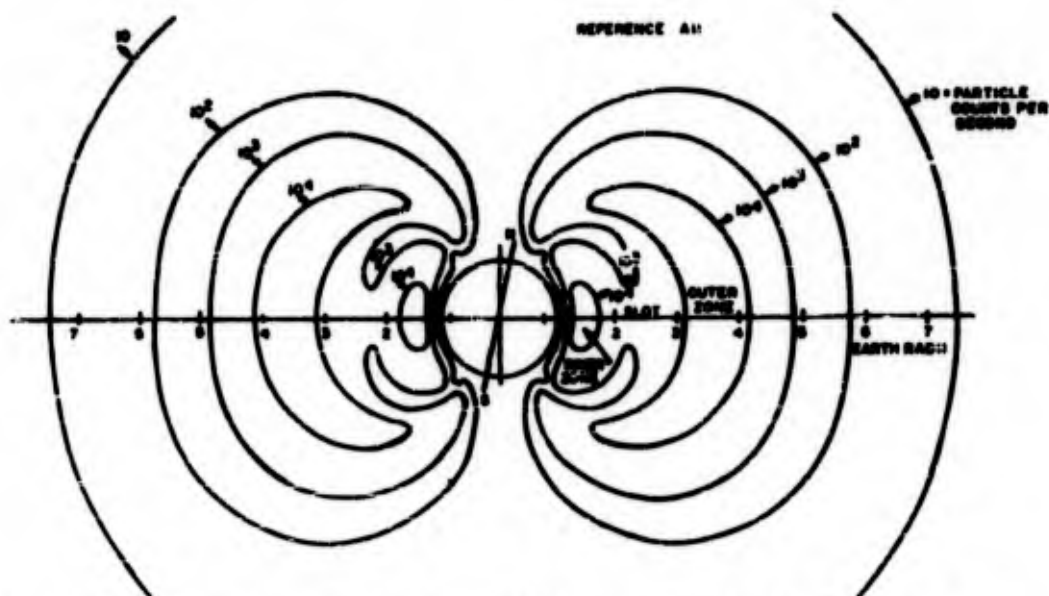


Figure 13. Structure of the Circumterrestrial Great Radiation Belt

Environment

It has been demonstrated conclusively that the composition and energy spectra of the components of the trapped radiation in the inner zone are quite different from those of the outer zone; the difference between zones is much greater than differences within a particular zone.

The intensity of the radiation in the inner zone decreases by a factor of ten between the ranges of 1 milligram per centimeter squared (mg cm^{-2}) (Reference C19). It falls off much more gradually at ranges greater than 140 mg cm^{-2} . (Range refers to the penetrating power of a particle, i.e., the particle would penetrate any material to a thickness at which a cm^2 column would have the weight indicated.) Of the radiation that penetrates at least 140 mg cm^{-2} , a small fraction of 1% also penetrates several g cm^{-2} (Reference C19). This more penetrating component is tentatively identified with protons of energies of the order of 100 million electron volts (MeV). The less penetrating component has a low specific ionization and therefore probably consists of electrons with energies up to about 1 MeV and having an energy spectrum rising steeply toward the lower energies (although not as steep as that of auroral soft radiation).

Total energy fluxes* as high as $100 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$ have been recorded beneath 1 mg cm^{-2} of shielding at an altitude of 1240 miles (inner zone) near the geomagnetic equator (one erg equals approximately $6.3 \times 10^5 \text{ MeV}$; a steradian (sterad) is a unit solid angle). As measured with a thin CeI crystal, more than 95% of this energy flux was in the less penetrating electron component (Reference C25).

The radiation rapidly becomes less penetrating as one progresses farther from the earth and in the outer zone was almost completely absorbed by the 4 g cm^{-2} of lead shielding placed on an Anton 213 counter in Pioneer IV. Table 2 (based on recent rocket studies of the lower fringe of the inner zone and of the extensive studies of Explorer IV and Pioneers III and IV), presents a tentative radiation composition for the heart of both the inner and outer zones (References C8, C11, C19, C25, C26, C27 and others). In Table 2 the maximum intensity of each component is given. The figures quoted in Table 2 for components whose intensity is given in particles per cm^2 per sec per steradian are maximum unidirectional intensities while those given in particles per cm^2 per sec are maximum omnidirectional intensities.

From its behavior during the periods of observation to September 1960, the inner zone remains relatively stable with time. However, there are marked temporal fluctuations in the slot and there are fluctuations of very great magnitude, with respect to both intensity and spatial structure, in the outer zone, particularly in the "horns" where the zone approaches closest to the earth's surface. Pioneer IV showed radiation intensities in the outer zone much greater than those recorded by Pioneer III. Pioneer III's data was taken during an especially quiet geophysical period while the flight of Pioneer IV was preceded by five days of continuous and intense solar unrest (Reference C12).

* Total energy flux is the product of individual particle energies and intensities.

Table 2

Comparison of the Tentative Composition Characteristics
of the Great Radiation Belt at the Heart of the Inner and Outer Zones *

Component	Inner Zone at ~ 2240 miles	Outer Zone ** at ~ 18,600 miles
Electrons		
energy > 2.5 MeV		$< 10^6 \text{ cm}^{-2} \text{ sec}$
energy > 200 KeV		$< 10^8 \text{ cm}^{-2} \text{ sec}$
energy > 20 KeV	$2 \times 10^7 \text{ cm}^{-2} \text{ sterad}^{***}$	$< 10^{10} \text{ cm}^{-2} \text{ sec}^{*****}$
energy > 600 KeV	$10^7 \text{ cm}^{-2} \text{ sterad}^{****}$	
Protons		
energy > 60 MeV		$< 1 \text{ cm}^{-2} \text{ sec}$
energy > 40 MeV	$2 \times 10^4 \text{ cm}^{-2} \text{ sec}^{****}$	
energy < 30 MeV	no significant information	
Estimated Shielded Dose Rates Includ- ing Secondary Radiation		
3.5 mm of lead (4 g cm ⁻²)	~ 10 r/hr	
1 g cm ⁻² of low atomic number (Z) material	~ 15-20 r/hr	~ 50 r/hr

*Numerical estimates shown are upper limits.

**The intensity figures quoted for the outer zone are based on periods of normal solar activity.

***This figure is probably reliable within a factor of 10.

****These figures are probably reliable to within a factor of 2.

*****This figure is for quiescent periods, during periods other than quiescent may approach 1×10^{11} particles per cm² per sec.

Estimates of the unshielded radiation dose rates within the zones have been made. These estimates depend on the assumed relative proportions of electrons to protons (not now well known) and range from 10 roentgens per hour (r/hr) maximum for 100% electrons to 100 r/hr maximum for 100% protons (Reference A18). Figure 14 illustrates one possible estimate of the dose rate versus altitude within the radiation belt at the geomagnetic equator beneath a 1 g cm^{-2} lead shield. Additional shielded dose rates will be discussed later.

Effects

The limited information available on the Great Radiation Belt has enabled estimates to be made of the radiation dose rates within the two zones. Depending on the relative proportions of protons and electrons, the estimates vary from a maximum of 100 r/hr for a 100% proton composition to 10 r/hr for a 100% electron composition. Figure 14 presents an estimate of dose rate versus altitude within the radiation belt at the geomagnetic equator. Wall thickness dictated by normal structural requirements for a vehicle traveling in a vacuum will produce a significant and in some cases a substantial reduction in the total intensity, however, the remaining intensity is usually large enough to present a problem to manned space flight. Besides possibly affecting the properties of certain materials these residual intensities within the vehicle may also affect the crew.

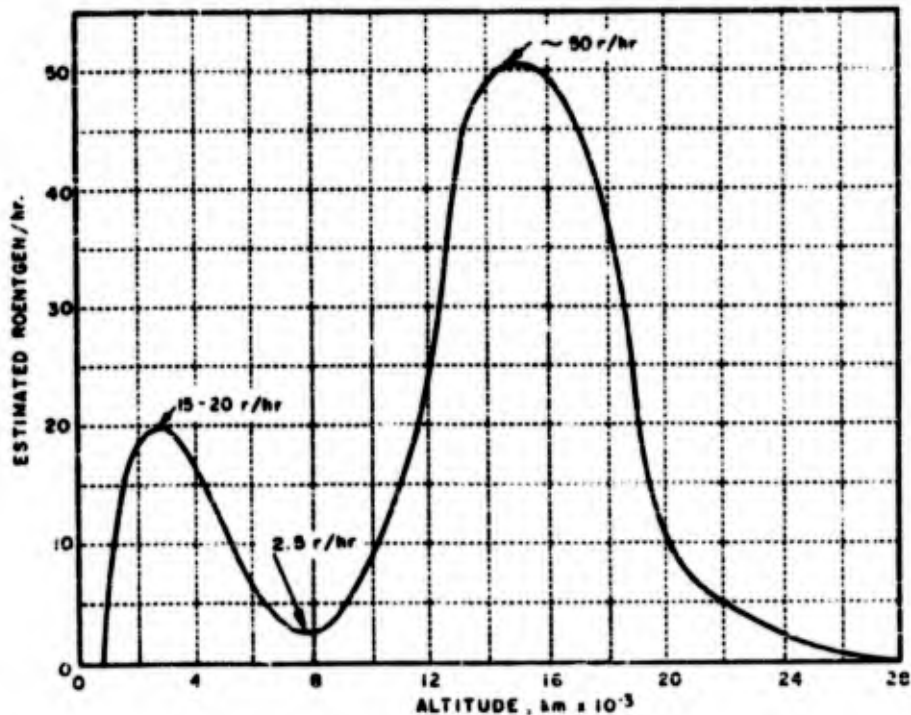


Figure 14. Estimated Dose Rate Beneath 1 g cm^{-2} of Shielding During Periods of Normal Solar Activity at the Geomagnetic Equator

Whole-Body Radiation. Behind a 3.5 mm lead shield, the maximum intensity within the inner zone is still of the order of 10 r/hr, therefore whole-body radiation is important. Present tolerance limits are based on statistical averages and as the quantity and quality of the data received change, the tolerances generally change. The present AEC whole-body maximum integrated dose is 0.3 roentgen equivalent man per day (rem/day) (Reference C13) which for electrons is equivalent to 0.3 r/day, or about 2×10^{-4} r/minute.

A human traversing the radiation belt will receive an integrated dose equal to:

$$\int_{t_0}^t \dot{R}(t) dt \quad (16)$$

where

$\dot{R}(t)$ = radiation dose rate

t = time

To remain within the radiation belt for more than a few minutes, it will be necessary to resort to mass shielding to reduce the dose rate within the vehicle to a tolerable level.

The two zones constituting the radiation belt have different characteristics. The inner zone is fairly stable; the outer zone fluctuates with solar activity. The inner zone, based on present estimates, has a greater concentration of protons than the outer (see Table 2).

Electron fluxes as high as 10^{11} electrons $\text{cm}^{-2} \text{sec}^{-1}$ prevail in the center of the outer zone. As a consequence, the dose rate inside the vehicle depends greatly on wall design and the material used since the largest part of the exposure within the vehicle will be produced by X-rays resulting from local bremsstrahlung* in the outer surface layers of the skin.

*Bremsstrahlung is the continuous X-ray spectrum wherein the intensities are independent of the target and the energy of the shortest wavelength is equal to the maximum energy of any electron hitting the target. Bremsstrahlung is proportional to the square of the particle mass and the intensity of production is directly proportional to the square of the particle energy times the atomic number of the target material. Thus whereas the X-rays produced are much more efficiently absorbed by substances of high atomic number on the same weight basis, the opposite holds true for heavy nuclei which are more strongly attenuated by atoms of low atomic number such as hydrogen.

Table 3 presents required shielding weights for two typical Beta X-ray shields

Table 3
(Reference A18)

Shielding from Beta Rays and Associated Bremsstrahlung X-Rays

Beta Ray Energy MeV	Weight of shield (lb/ft ²) for 95% absorption	
	Plain Lead	Combination Lead plus Plastic
0.05	1.224	0.245
0.5	61.2	12.24
5	175.5	38.76

Estimates of the mass shielding required to attenuate the radiation to a tolerable level neglecting the bremsstrahlung-produced X-rays have been made (see Figure 15) and from these it can be seen that the weight penalty

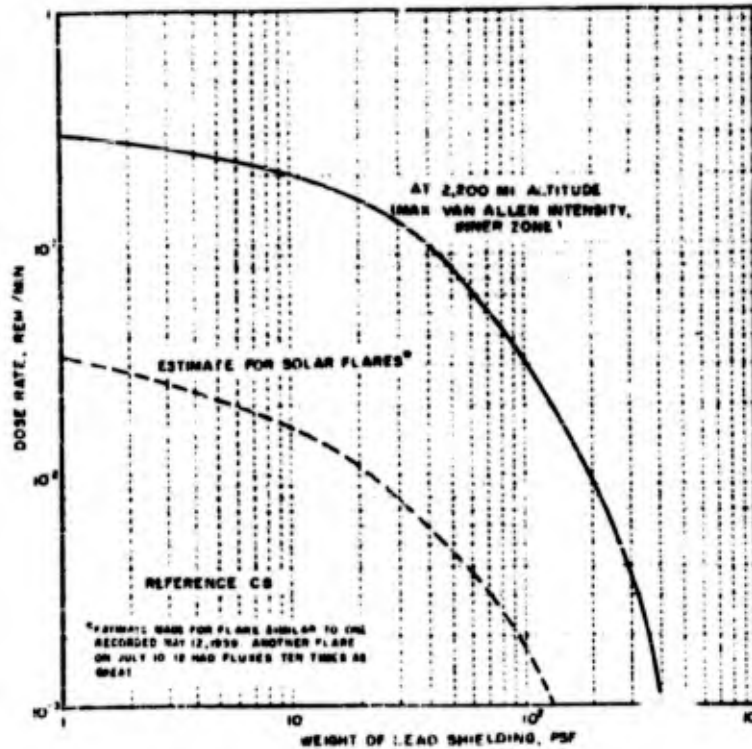


Figure 15. Estimated Minimum Weight in Lead Required Reduce the Whole-Body Dose Rate for Human Beings in Space to the Indicated Levels, Neglecting Secondary Radiation

imposed is enormous. To decrease the maximum inner zone intensity to a human tolerable level will require in excess of 400 lbs. of lead shielding per square foot of interior surface area (surface area of the interior wall of the compartment being shielded). For the outer zone, a lead shield weight in the neighborhood of 90 lbs. per square foot of interior surface area would be required during periods of normal solar activity. During periods of increased solar activity, the shielding weights for the outer zone would have to be increased.

The above estimates were based on a lead shield and consequently may not be the minimum shield weight required, but they are an indication of the order of magnitudes involved. For example, the use of hydrogen (see Figure 16) requires only 20% as much shield weight as lead to stop protons. But in doing so, the protons produce more gamma rays. The additional shielding required to stop the gamma rays adds sufficient weight that the total weight saving compared to lead is almost negligible. Secondary radiation, sometimes of higher ionizing ability than the primary, is a possible serious consequence of mass shielding, and it may be required that the structure be a laminate of materials having high and low atomic numbers.

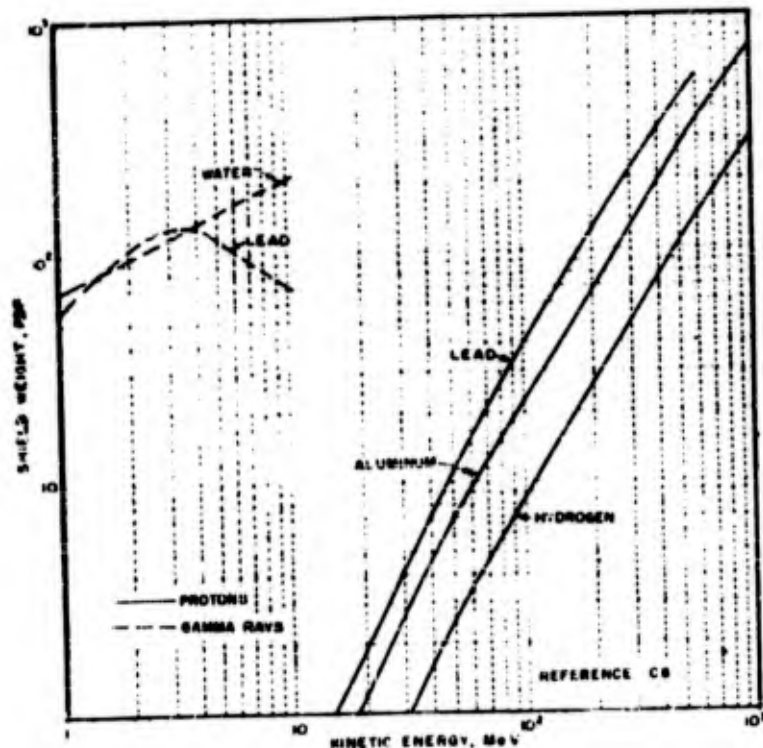


Figure 16. Weight or Shielding Requirements to Stop Protons and to Decrease Gamma Ray Intensity by 90%

The present state of shielding technology has not developed an "active" shield (i.e., the application of artificial magnetic fields or charged bodies) and therefore for the lack of anything else mass shielding is required.

Material Properties. The effects of radiation on the physical properties of materials have been studied but in many instances the data are conflicting. Seemingly, structural materials are insensitive to radiation except at extremely high intensities. Even at the peak intensities recorded in the belts, metals would remain unchanged for many years. Reinforced plastics with a minimum radiation damage threshold of nearly 10^6 radiation absorbed dose (rad) would be unaffected except over very long periods of exposure. Solar batteries and semiconductors may be affected as it has been demonstrated that the combination of radiation darkening the quartz windows protecting the solar cells and radiation changing the physical characteristics of the cell may result in the solar cells becoming inoperative in about one year if they are operating entirely within the radiation belt. Similarly, recent estimates disclose that damage to a transistor would become excessive after an orbital time of 8 months in the radiation belts. Transient effects may also be produced in semiconductors; in most cases, the current data is of questionable quality and no definite effects can now be stated.

Primary Malfunctions

The malfunctions that may occur for a manned flight through or within the Great Radiation Belt are as follows:

1. Radiation sickness of one or more members of the crew with the remote possibility of death occurring. In event of this happening, the efficiency of the crew would be impaired resulting possibly in mission failure.
2. Transient or permanent damage to electronic equipment (of considerably less likelihood). The effects resulting from this type of malfunction depend on the equipment affected.

Aspects Requiring Simulation

The following aspects of the environment within the Great Radiation Belt require simulation:

1. The expected radiation levels within the space cabin. This must be simulated passively (e.g., a meter reading both dose rate and integrated dose) since simulation by actual exposure of the crew would prove harmful.
2. Any expected transient effects in the electronic equipment. In a well-designed vehicle, no permanent damage is anticipated.

LOW-ALTITUDE RADIATION (AURORAE PRODUCING PARTICLES)

Several detailed theories of the emission of the auroral spectrum have been presented by various investigators. Most of these depend on a collision process in which a secondary electron, liberated from an atmospheric molecule or atom by the incoming particles, gives up its kinetic energy to excite another molecule or atom; this excitation is then followed by emission. For example, Meinel (Reference A5) concludes that fast protons entering the upper atmosphere inject electrons in sufficient numbers and with moderate energy that on impact with atmospheric atoms and molecules, they give rise to the greater part of the auroral luminosity.

Environment

The intensity of the trapped radiation in the near vicinity of the earth seems to obey an inverse relationship, being highest at the latitudes where the protection due to the geomagnetic field is at its peak and zero where there is no such shielding. A peculiar feature of this radiation is the altitude structure of the radiation belt just previously discussed. At its high latitude edge, where the critical configuration for stable trapping seems to reach into the ionosphere and upper mesosphere, the particles collide with the air molecules and atoms and produce aurorae.

According to Van Allen, auroral fluxes approaching 10^8 electrons/cm² sec. are not uncommon but the energy of the electrons seems to be limited to values in the range from about 10 to 100 thousand electron volts (KeV); therefore the penetrating power is small. The upper energy limit of 100 KeV may still be open to question. Winckler and Peterson (Reference C31) and Anderson (Reference C32) have observed auroral X-rays at balloon altitudes of 8 g cm⁻² and 11 g cm⁻² residual atmospheric pressure respectively. Thus it seems that the primary intensity must have been enormous during these observation periods.

Van Allen estimates that the upper limit of the photon flux in an auroral display at 10^5 photons cm⁻² sec. Anderson reported measuring a photon flux of 20 photons cm² sec. at balloon altitudes.

Winckler and Peterson have directly measured the total ionization during the aurora and found, at balloon altitudes far below the actual aurora, a dose rate of 5 milliroentgen equivalent physical per hour (mrep/hr.).

Effects

The intensity of the soft auroral radiation is much less than that of the Great Radiation Belt. Consequently, the only non-negligible effect presently foreseen is whole-body radiation and no change in material properties is expected.

Whole-Body Radiation. In attempting to evaluate the data presented on the soft auroral radiation in terms of tissue dosage, it is necessary to recognize that a man traveling through auroral displays will never be exposed freely to the radiation. In addition to the vehicle structure, he would be garbed in heavy clothing. Due to the limited penetrating power of the radiation in question, these will afford substantial protection by attenuation. For example, using Van Allen's (Reference A18) estimate for the electron flux as 10^8 electrons $\text{cm}^{-2} \text{sec}^{-1}$, the air dose rate is enormous, namely 2.5 rep/sec. Yet since these electrons are limited to the energy range from 10 to 100 KeV the penetrating power will not exceed 1/10 mm of Bakelite.

However, secondary radiation resulting from local production of X-rays in bremsstrahlung processes tends to defeat the protection from primary radiation that the vehicle offers and may increase the penetrating power of the radiation by about one thousand times. Therefore, shielded dose rates could be significant.

A major factor reducing the radiation exposure in flight through aurorae will be the limitation on exposure time. Since aurorae are heavily centered at an altitude of about 100 km, vehicles on lunar or interplanetary flights will pass through the auroral region at speeds of the order of 10 km/sec, which should enable a vehicle to pass through a large display in minutes. Little is known, however, about the flux density and geometrical configuration of the particle stream behind the luminescent part of an aurora. If this extends for large distances with a sizeable flux, a significant radiation dosage may result. The problems for a satellite are different. Here the vehicle may repeatedly traverse an auroral region. (Although, by virtue of orbital mechanics and restriction of aurorae to high latitudes, it is estimated that exposure can never exceed more than 30% of the possible full dose.)

A further and probably the most important reduction of the exposure dose is due to the time limitation and the intensity variations of the phenomenon. At any arbitrarily selected altitude, latitude and longitude in the auroral belt, peak intensities seem to prevail for comparatively short times. Naturally, these variations in space and time are of a statistical nature and therefore cannot be predicted, except for the general long-term correlation to the solar cycle. In view of these circumstances, constant monitoring of the exposure may be necessary for a manned satellite in an orbit of high inclination from the equator.

Primary Malfunctions

The only malfunction presently foreseen as resulting from aurorae-producing particles is the very remote possibility that one or more crew members may perform inadequately as a result of excessive radiation exposure.

Aspects Requiring Simulation

For an earth satellite in an orbit of high inclination with the equator the expected radiation exposure within the auroral belt should be simulated. This could be done by artificial readings on a dosimeter.

GALACTIC AND SOLAR COSMIC RAYS

It is generally accepted that almost all primary galactic cosmic radiation reaches the vicinity of the earth-moon system from outside the solar system. The sun is an additional source of low energy "cosmic" rays and further, through its magnetic field, acts as a modulating agent for all low-energy particles. As will be seen, during certain periods, the sun may inject a markedly increased flux of protons into the solar system.

Environment

Sufficient evidence has been gathered to demonstrate conclusively that primary galactic cosmic radiation is composed of positively charged particles (protons and nuclei of heavier elements) almost isotropically distributed in space (to within about 0.05%) and with a continuous spectrum of energy extending up to at least 10^{18} eV.

Long before entering the earth's atmosphere, the cosmic ray primaries, being electrically charged particles, are subjected to the influence of the earth's magnetic field, which modifies their trajectories. A particle of charge Z times the elementary charge e , traveling with momentum p perpendicular to the magnetic lines of force of flux density B , is deflected, following a trajectory whose radius of curvature R is given by:

$$R = p/300 BZ \quad (17)$$

where

R is in cm

p in eV/c (c = particle velocity)

B in gauss

The quantity $M = 300RB$ = momentum/charge in volts is often referred to as the "magnetic rigidity".

Primaries approaching the vicinity of the earth along the magnetic axis will not be deflected; on the other hand, the deflection will be maximum for those trajectories in the geomagnetic equatorial plane (momentum at right angles to the lines of force).

Table 4 shows the relative composition of primary galactic cosmic radiation in the vicinity of the earth outside the atmosphere.

Table 4

Relative Abundance of Particles Composing Galactic Cosmic Rays

Element	Charge	Abundance Relative to that of Hydrogen	
		Cosmic	Universe
H	1	1	1
He	2	10^{-1}	10^{-1}
Li	3		
Be	4	$\sim 10^{-3*}$	0.4×10^{-8}
B	5		
C	6	5×10^{-3}	1.3×10^{-3}
N	7		
O	8		
	$9 \leq Z \leq 30$	2×10^{-3}	$\sim 10^{-3}$
	$30 \leq Z \leq 92$	$< 10^{-5}$	3×10^{-5}

The direction of arrival of the primaries from the celestial sphere is isotropic to better than one percent for all the known particle energy spectra, and the average intensity is constant in time. The flux P in the neighborhood of the earth, but corrected for the effect of its magnetic field, (with an uncertainty by a factor of 2 or 3), is: $P = 3.5 \times 10^{-3} \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1} \sim 25, \text{ millirad day}^{-1}$. The corresponding energy density is $D = 4 \pi P/c = 1.5 \times 10^{-12} \text{ erg cm}^{-3} \sim 1 \text{ eV cm}^{-3}$ which is approximately the energy density for starlight.

On the average, the flux of cosmic rays is constant in intensity and composition, and, at least up to 10^{17} eV , highly isotropic in the space surrounding the earth. Figure 17 presents the energy spectrum associated with the primary galactic cosmic ray components. However, fluctuations in the galactic cosmic ray component, do exist. These fluctuations are usually designated "time variations"; "solar" the ones in relation to the sun, "sidereal" those in relation to the celestial sphere.

*There is some doubt about this value owing to uncertainty in the correction for the extrapolation of the flux outside the atmosphere.

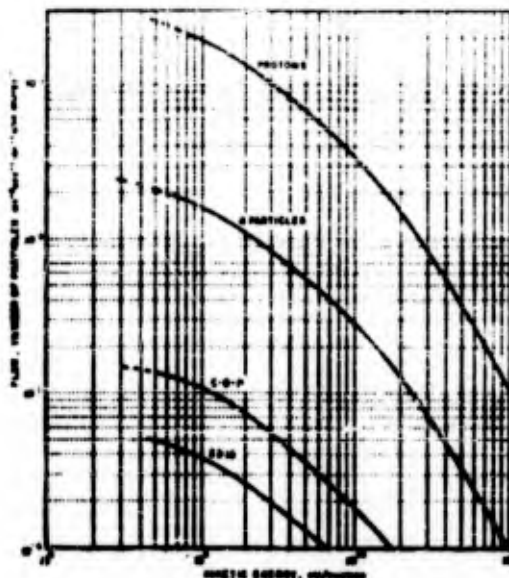


Figure 17. Primary Integral Energy Spectrum of Cosmic Rays

The sun definitely appears to be both a source of and a modulation agent for low energy cosmic rays ($\leq 10^{11}$ eV); this fact has been established on the basis of the following variations in the total intensity correlated with solar phenomena.

1. Periodical fluctuations of the order of a few percents or fractions of a percent, with the following periods of recurrence:
 - a. Diurnal
 - b. 27 days (rotation of sun about its axes)
 - c. 11 years (cycle of solar activity)
2. Occasional fluctuations:
 - a. Frequent increases of the order of one percent in correlation with small solar flares.
 - b. Large increases (up to a factor of 50 and more) associated with great solar flares.
 - c. Decreases consequent to magnetic storms of solar origin.

No definite evidence exists for variations with a recurrence related to a sidereal time. Such variations, if they existed, would indicate the existence of an irregular distribution of sources in the sky or a diffusion of cosmic rays from the galaxy. Such does not seem to be the case.

Further data related to the solar variation of cosmic ray intensities was released in August 1959 by University of Minnesota physicists Ney, Winckler, and Frier, who reported that lethal levels of solar cosmic radiation had been registered in May and July 1959 by balloon borne instrument packages (Reference C18). During this event, the integrated flux of particles at the top of the atmosphere increased by approximately a factor of 1000 above that of normal cosmic ray levels and the composition of the incoming beam as observed at 10 g cm^{-2} atmospheric depth was essentially pure hydrogen. The measured flux of alpha particles and heavy nuclei was not increased and corresponded to the normal cosmic ray flux at solar maximum. However, if the sun-injected heavy particles had the same rigidity spectrum as the protons observed, the atmospheric cutoff would have prevented their detection at the 10 g cm^{-2} atmospheric depth where the measurements were taken.

The energy spectrum was of the form: (Reference C18) $N(E)dE = KE^{-6.8}$ in the measured range of $110 \text{ MeV} < E < 220 \text{ MeV}$. The corresponding integral rigidity spectrum was $N(>R) = 7,500R^{0.6}$ with R (magnetic rigidity) in billion electron volts (BeV) and $N(>R)$ in protons/m²/sec/ster.

A balloon observation, made at the peak of the intense period of July 15 recorded an exposure level of nearly 0.2 r/hr beneath 4 g cm^{-2} of residual atmosphere (Figure 18). Depending on the shape of the spectrum at low energies, but under a reasonable assumption, the unshielded intensity of the particles in outer space at this time could have been at least 100 and possibly as high as 500 r/hr.

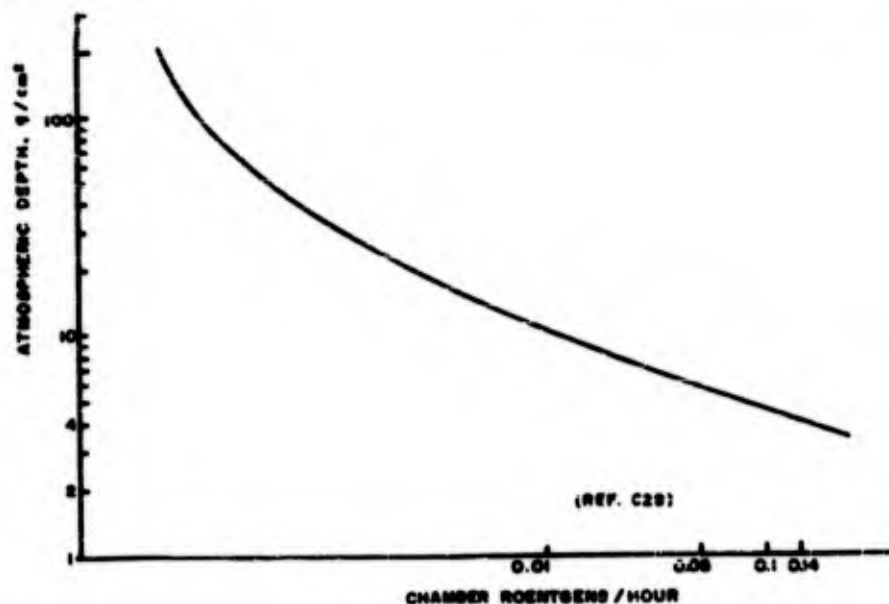


Figure 18. Altitude Dependence of Solar Induced Radiation Intensity on July 15, 1959

This much is certain, the large increases in cosmic ray intensity noted in the stratosphere at northern latitudes are due to primary protons of solar origin. The proton energies obtained from measurements at geomagnetic latitude 64° exceed 100-120 MeV. For five cases observed in 1959 (May 11-15, July 8, 10, 14 and 16) the solar cosmic-ray outbursts were preceded by chromospheric flares of the highest power 3+. The cosmic-ray outbursts registered on these dates correlate with the magnetic storms with sudden commencement and the Forbush-decreases* in cosmic-ray intensity on the earth. The delay time between the observation of the flare and the arrival of solar protons at the earth ranged from one to seven hours. The outbursts observed had a duration of a few days.

Effects

The effects of cosmic rays and solar protons are very similar to those resulting from the previously described radiation sources. Two hazards are known to be present; the first is direct tissue destruction and the second whole-body radiation. A third may arise from reaction of penetrating cosmic rays with the internal atmosphere although this has not yet been substantiated. Effects on materials can be entirely neglected during normal solar activities because of the relatively low radiation levels involved.

Tissue Destruction. The heavy primary cosmic rays are relatively few in number (constituting less than 1% of the total particle flux). However, they constitute a danger because they are heavily ionizing and can destroy biological tissue. When a heavy primary comes into contact with human tissue, it will destroy a small cylindrical volume of tissue to a depth of about 50 microns. This destroyed volume is small but some vital tissue may be destroyed which will temporarily or permanently immobilize the human.

Whole-Body Radiation. During periods of solar activity similar to that noted by Ney, Winckler and Frier (Reference C13) during May and July of 1959, whole-body radiation becomes a problem. The radiation dose rate measured beneath 4 g cm^{-2} of residual atmosphere, for ranges of protons in various media see Figure 19, was nearly 0.2 r/hr during one period of high intensity (Reference C18). Depending on the shape of the spectrum at low energies, but under a reasonable assumption, the intensity of the particles in outer space at this time was probably about 100 r/hr.

During a period of high intensity, 15 July 1959, the amount of residual atmosphere required to reduce the whole-body radiation of the present AEC standard of 0.3 roentgen equivalent man per day (rem/day) was about 15 g cm^{-2} . This indicates that the mass shielding required to adequately attenuate the radiation to a tolerable human level would be of the same order of

*The Forbush phenomenon is believed to be due to the perturbed Sun's magnetic field. The magnetic "cloud" causes the galactic cosmic rays to be veered from the earth causing a temporary decrease in intensity at sea level.

magnitude, but at least as great, and probably greater, as that required for the outer zone of the radiation belt during normal solar activity. It is thus impractical to mass-shield vehicles for the purpose of attenuating this radiation.

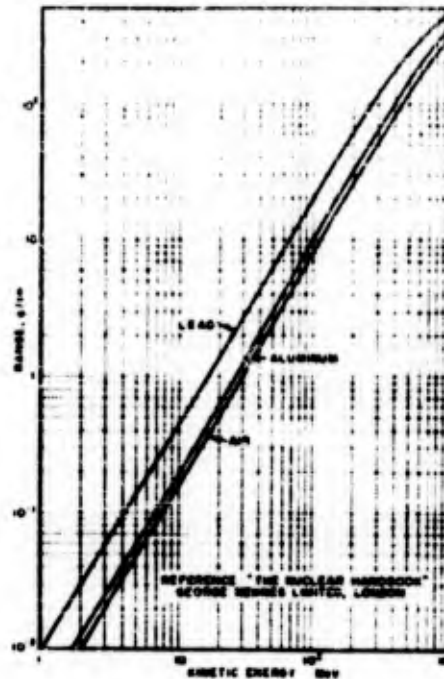


Figure 19. Range of Protons in Lead, Aluminum and Air

Five events of approximately equal intensity have been noted since 1946. However, during this same period forty events of less spectral intensity have been known to occur and these too present a whole-body radiation problem (during the past three years, a period in the solar cycle when maximum activity occurs, twenty-five cases of intense cosmic ray activity have occurred). Further measurements and evidence are needed before these events can be classified as a serious restriction to space missions, although presently it is indicated to be a restriction. Figure 16 presents an estimate of the minimum weight of lead shielding required for a solar flare similar to the intensity measured 12 May 1959 which was about one-tenth the intensity measured 15 July 1959.

Atmospheric Ions. Cosmic rays penetrating into the cabin may react with the cabin atmosphere and by the process of atomic disintegration give rise to ions of moderate atomic weights. Recent research* demonstrated that these ions will have neither a deleterious nor exhilarating psychological effect.

*Chiles, W. Dean; John M. Cleveland and Richard E. Fox, Study of the Effects of Ionized Air on Behavior, WADD Technical Report 60-598, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio, November 1960.

Primary Malfunctions

The malfunctions presently foreseen as resulting from the cosmic ray and solar proton environment of space are due to its possible effects on the crew. Whole-body radiation induced by an unexpected blast of lethal radiation of solar origin could, even in a well-designed space vehicle, cause one or more crew members to contract radiation sickness resulting in temporary or permanent incapacitation. The probability that the non-solar primary cosmic rays would cause temporary or permanent incapacitation of one or more members of the crew also exists.

Aspects Requiring Simulation

The radiation environment should be simulated. Because active simulation would prove harmful to the participating subjects, some form of passive simulation must be used. Both the integrated dose and dose rate should be displayed. During the simulation, the emergency procedures necessary to protect the crew against solar-injected protons similar to the one recorded during May through July 1959 should be included.

ADEQUACY OF EXISTING DATA

Particulate radiation can have most serious consequences to manned space flight and, is one area where further data is especially desired. The data presently available presents an incomplete space-time description of the Great Radiation Belt and also fails to disclose the relative importance of the solar induced radiation similar to that recorded in May and July by University of Minnesota scientists. Data are especially meager in the following areas:

1. The energy level, number, and kind of particles in the radiation belt and their variation with altitude, angular position and time.
2. Similar data for solar disturbances.

Additional data is also desirous on particulate radiation effects in the following areas:

1. The effects, both permanent and transient, of radiation intensities equal to those present within the Great Radiation Belt on semi-conductor materials.
2. The effects resulting from the interaction of two or more environmental factors, e.g., the effects resulting from combined particulate and EM radiation on materials.

GASEOUS MEDIUM (LOW-ENERGY PARTICLES)

Although interplanetary space is a very high vacuum, it definitely cannot be considered empty, abounding with numerous macroscopic solid bodies, dust particles and gaseous components. The last category is of interest here.

ELECTRONIC, IONS AND NEUTRAL PARTICLES

The gaseous medium consists of electrons, ions and neutral particles. The atomic composition is predominately hydrogen, followed by helium. Atomic oxygen and nitrogen may also exist in detectable concentrations.

Environment

The total density of all gaseous components in space is estimated to be somewhere in the range of 100 to 1000 particles cm^{-3} although it may be well above or below these figures because of the uncertainties involved. Hydrogen and helium are the two most abundant elements in the universe and therefore it is expected that most of the gaseous content in space will consist of these two elements in ionic, atomic, or molecular form. I. S. Shklovski has estimated that the gaseous content of interplanetary space contains about 0.5 atoms cm^{-3} of neutral hydrogen and nearly 200 atoms cm^{-3} of ionized hydrogen (References D7, D8); other observers (Reference D1) estimate the mean density of neutral hydrogen to be nearer 0.2 atom cm^{-3} .

The concentration of free electrons in the neighborhood of the earth is estimated to be about 600 cm^{-3} and increases to about 10^4 cm^{-3} at a distance of 0.1 astronomical unit (AU) from the sun (Reference D8).

Figure 20 presents one estimate of the mean density of the atomic hydrogen cloud in the near vicinity of the earth.

Effects

The absence of an appreciable atmosphere and the presence of some gaseous media in space produce effects on the vehicle's surface that may not be negligible. The high vacuum in space has two important effects on solid materials, namely, sublimation and evaporation and the partial or complete removal of the surface film of gas which ordinarily covers all materials. The presence of a gaseous medium has one significant effect, namely atomic and molecular sputtering. Little is presently known of the magnitude of any of these individual effects, but over-all the total effect is a possible change in the surface optical properties and perhaps a change in the structural properties of the surface material.

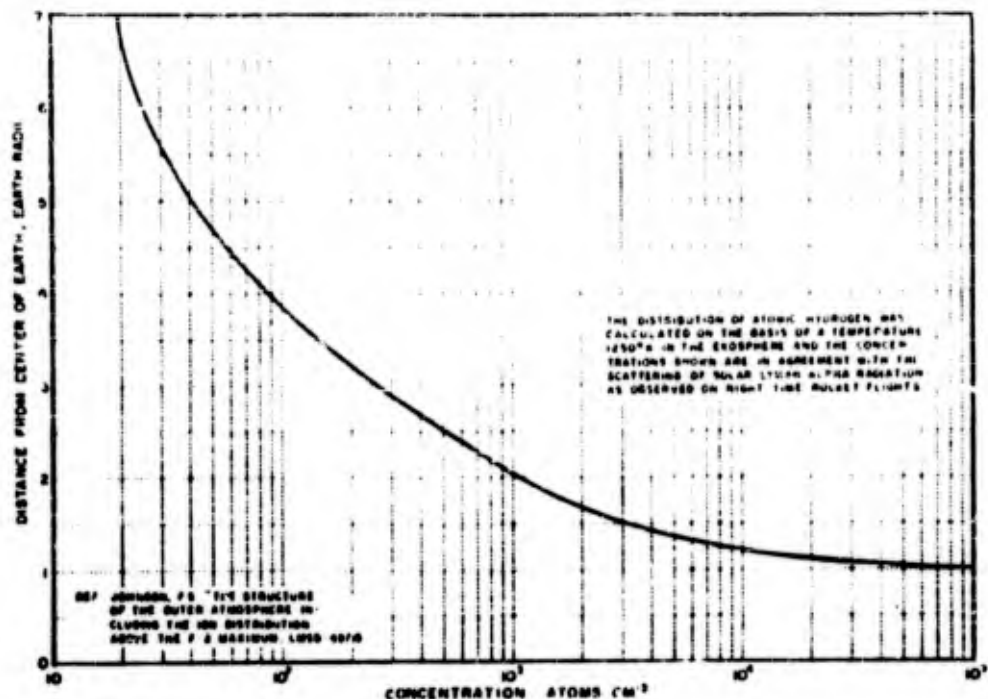


Figure 20. Density of the Hydrogen Cloud Around the Earth

Sublimation and Evaporation. Sublimation and evaporation are enhanced by the absence of an atmosphere in that molecules leaving the surface of a material are not counter-balanced by an appreciable number of molecules returning through surface collisions. Therefore, if a vehicle is at an altitude such that the mean free path of the molecules is long compared to the size of the craft (roughly 100 miles), any molecule that leaves the surface can be assumed not to return.

The rate of vaporization varies rapidly with temperature, since it is a function of vapor pressure, which varies as the exponential of $1/T$, (Reference D3). The Langmuir equation for the rate of vaporization of a pure material is:

$$G = \sqrt{\frac{M}{T}} \cdot \frac{P}{17.4} \quad (18)$$

where

- G = rate of loss in g sec-cm⁻² of exposed surface
- M = molecular weight of material
- T = temperature, °K
- P = vapor pressure in mmHg at temperature

Applying the above equation to typical elemental metals discloses that few will lose appreciable material at temperatures much below their melting points, although there are some very important exceptions (e.g., magnesium), see Table 5.

Table 5
Maximum Vaporization Losses Computed
from Langmuir Equation for Variety of Metals at
50 and 75 Percent of Their Absolute Melting Point (Reference D4)

Metal	Melting point °F	50% of absolute melting point		75% of absolute melting point	
		Temperature °F	Loss (inches per year)	Temperature °F	Loss (inches per year)
Carbon	6700	3120	7.5×10^{-5}	4550	21.7
Tungsten	6170	2855	2.9×10^{-9}	4180	4.2×10^{-3}
Tantalum	5425	2480	3.6×10^{-11}	3660	3.3×10^{-4}
Molybdenum	4760	2150	1.4×10^{-8}	3195	1.1×10^{-2}
Niobium	4380	1960	4.6×10^{-15}	2930	1.5×10^{-6}
Chromium	3272	1405	2.0×10^{-3}	2150	115
Platinum	3224	1380	8.4×10^{-14}	2120	3.5×10^{-6}
Iron	2800	1170	7.7×10^{-9}	1820	1.4×10^{-2}
Cobalt	2723	1130	8.1×10^{-12}	1770	8.7×10^{-5}
Nickel	2650	1095	2.1×10^{-11}	1720	2.9×10^{-4}
Beryllium	2340	940	1.6×10^{-9}	1500	6.6×10^{-3}
Aluminum	1220	380	4.8×10^{-23}	715	2.6×10^{-12}
Magnesium	1200	370	1.0×10^{-3}	700	53

The effect of the loss of one component from an alloy is much more difficult to predict. Raoult's law, found in any text on high vacuum principles (e.g., Reference D3), will give some indication as to the rate of loss of one component but the exact changes involved must be found experimentally. The experimental results thus far published are inconclusive as most exposure times have been relatively short (approximately 24 hours) and in some instances the results contradictory.

Plastics, containing more ingredients, are more complex than metals. Although the basic polymer of the plastic is not likely to have a high enough vapor pressure to cause significant loss of material, some of the other ingredients may. In particular the plasticizers used in many plastics have

relatively high vapor pressures. Table 6 shows vapor pressures and loss rates for typical plasticizers as calculated from Equation 1. Because the rate of diffusion of the plasticizer inside the plastic is also important, and since in a number of cases the exact constitution of the plastic is not known, experimental results are necessary to determine the effect of vacuum exposure on plastics.

Table 6
(Reference A9)
Loss of a Typical Plasticizer to Space

	Room Temperature	100°C
Vapor Pressure (mm Hg)	10^{-4} to 10^{-2}	0.1 - 1.0
Loss (g cm ⁻² -day)	1 - 100	1000 - 10,000

Probably of more importance than the expected loss of metals and plasticizers is the fact that lubricating oils may evaporate and certain gases will escape from their containers over a long period of time. The lack of sufficient data precludes comment on the significance or order of magnitude of these effects.

Removal of Gaseous Surface Film. If it is assumed that a film of gas on the surface of a material influences its mechanical properties (as indicated by some evidence, e.g., Reference A9), then the removal of this film may have an adverse effect. It is difficult to predict what kind of a gas film will form on the vehicle; the surface temperature, position in space and means of getting there are all important. However, since it is not possible to discuss the effect that all gas films have on materials (all of which can be studied under controlled laboratory experiments) only some general statements can be made. Recently, Shahinian and Achter (Reference D6), have shown that the density of the gas surrounding creep-rupture specimens affects the time required for the specimens to rupture and Wadsworth and Hutchings (Reference D9) have shown that the density of the surrounding gas seriously affects the fatigue life of certain metals. Both groups attribute these effects to the formation or depletion of surface layers of gas.

Atomic and Molecular Sputtering. Theoretical considerations indicate that ions and atoms of equal energy produce the same amount of sputtering from metal surfaces, since an ion is neutralized by an electron from the metal surface before it encounters other surface atoms. Actually, there is an additional attractive force produced by the opposite image charge in the metal, but this is so small it is usually neglected. Yield ratios for ions are higher for oblique angles of incidence than for normally incident ions. Presently, no evidence is available that sputtering by high altitude atmospheric atoms will or will not be a problem.

Ion sputtering (etching) has been studied more extensively. The etching rate, due to interaction with interplanetary gas, for the Sikhote-Alin meteorite fall was estimated to be $\leq 2 \times 10^{-7}$ cm/year (Reference E13). At an altitude of 250 miles above the earth's surface, where the concentration of ions and atoms is greater but the energies are less, it has been estimated that the etching rate is $\leq 10^{-8}$ cm/year. These losses are small and insignificant with respect to reduction of structural strength or rigidity but, when combined with other erosive effects, may significantly alter the optical properties of the vehicle's external surface.

Whipple (Reference E18) assumes meteoritic etching is due solely to sputtering from solar protons and normal incidence sputtering yields for protons on iron are as follows: 0.5 atom/proton for 10,000 eV or more, 0.2 atom/proton at 500 eV and ~ 0.02 atom/proton at 100 eV. In actual calculation, these are doubled to account, approximately, for the greater yields which are manifest at smaller angles of incidence.

Primary Malfunctions

A well-designed vehicle will reduce the possible malfunctions that can be caused by the space environment to a minimum. Most of the problems arising from the gaseous medium are due to the lack of an appreciable gaseous content and not from the constituents of which it is composed. Consequently, the vehicle can be designed to take into account the high vacuum and therefore presently no malfunctions due to the gaseous medium can be foreseen.

Aspects Requiring Simulation

The lack of an appreciable gaseous medium poses problems for the vehicle designer, but as presently envisioned no aspects of the environment require simulation for the purpose of training space crews.

ADEQUACY OF EXISTING DATA

Presently, little is known about the constituents of which the gaseous medium is composed nor their densities; however, further data, although desirable, will probably not significantly alter the magnitude and significance of the problems presently foreseen from available data as resulting from the medium.

It is desirable, however, to obtain data on:

1. The effects of a vacuum environment on the material properties of metals and non-metals and
2. The significance of atomic and molecular sputtering of metals and metallic oxides.

CONDENSED MATTER

The Earth is constantly being bombarded at an exceedingly high rate by pieces of stone and metal. In fact, the Earth collects many thousands of tons of material per day. Luckily for we terrestrial beings, it is the smallest and most insignificant particles which are most plentiful.

Whereas on earth we are protected by a vast atmosphere, a vehicle in space has no protection other than the structure of the vehicle itself. The effects these particles will have on the vehicle can at the present time be only theorized as no direct experimental data exists.

METEORITES, METEORS AND DUST

The condensed matter existing in space can be classified, in order of decreasing size, into: meteorites, meteors, and dust. Meteorites include those relatively large solid fragments that move in low eccentricity orbits about the sun and are large enough to descend through the earth's atmosphere without being completely destroyed by heat. They reach the earth's surface in sizes ranging from a few ounces to many tons.

Meteors covers a group of fragments which, upon entrance into the earth's atmosphere, do not in general survive passage, but do produce either a visible or ionisation phenomenon. These range in size from a fraction of a centimeter to one or two centimeters in diameter.

Dust, which includes micrometeorites, range in size from 10^{-2} to less than 10^{-4} centimeters in radius. They are too small to be observed during their passage through the earth's atmosphere and are slowed down high in the atmosphere without losing much of their mass by vaporization. They settle slowly to the surface of the earth.

Environment

Information about the size and number of meteorites, including meteors, roaming the solar system has come from visual, telescopic, and radio observation of the luminous and electrical phenomena produced by their interaction with the atmosphere, examination of the particles reaching the ground and a few meager measurements from high altitude rockets and satellites. Various estimates of the size, mass, and frequency of appearance of meteoroids in space have been made and these estimates vary by as much as several orders of magnitude, (see Figures 21, 22, 23 and 24) (Reference E3).

The earth moves in its orbit about the sun at a mean velocity of nearly thirty kilometers per second while meteorites moving on highly eccentric orbits can have velocities as high as forty-two kilometers per second. Depending on whether the meteorite collides in a head-on collision or catches up to the earth from behind, the relative velocity with respect to the earth can vary from seventy-two to eleven kilometers per second.

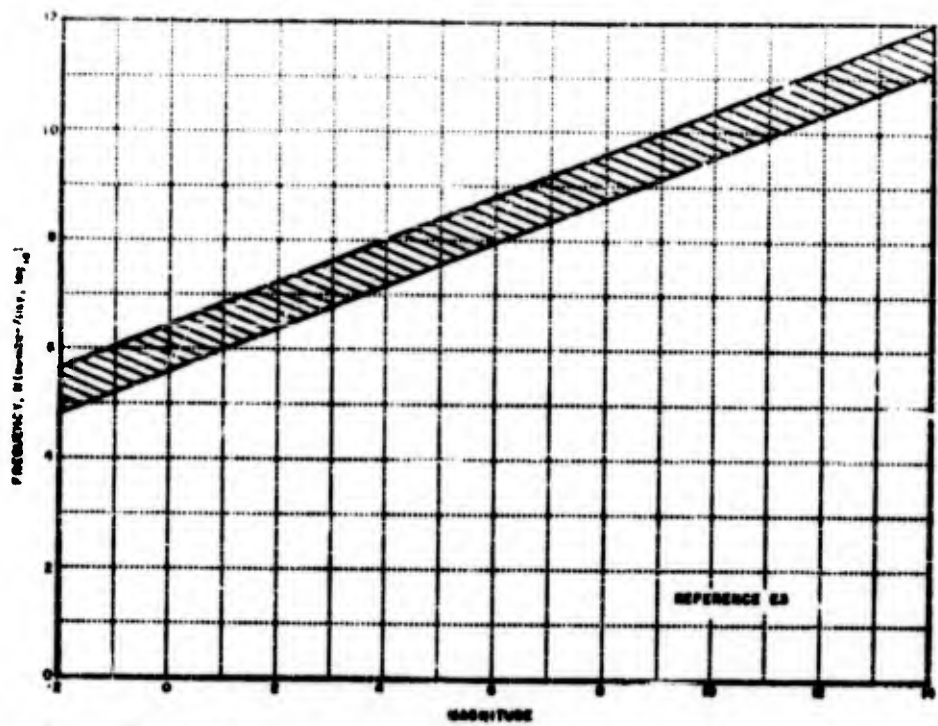


Figure 21. Observed Daily Frequency of Meteors in Earth's Atmosphere

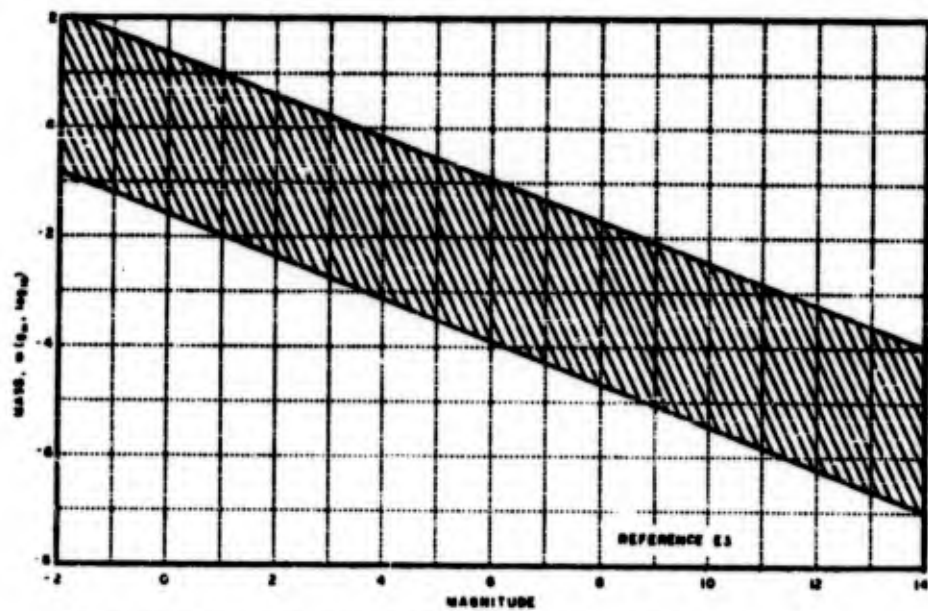


Figure 22. Estimated Meteorite Mass Per Magnitude

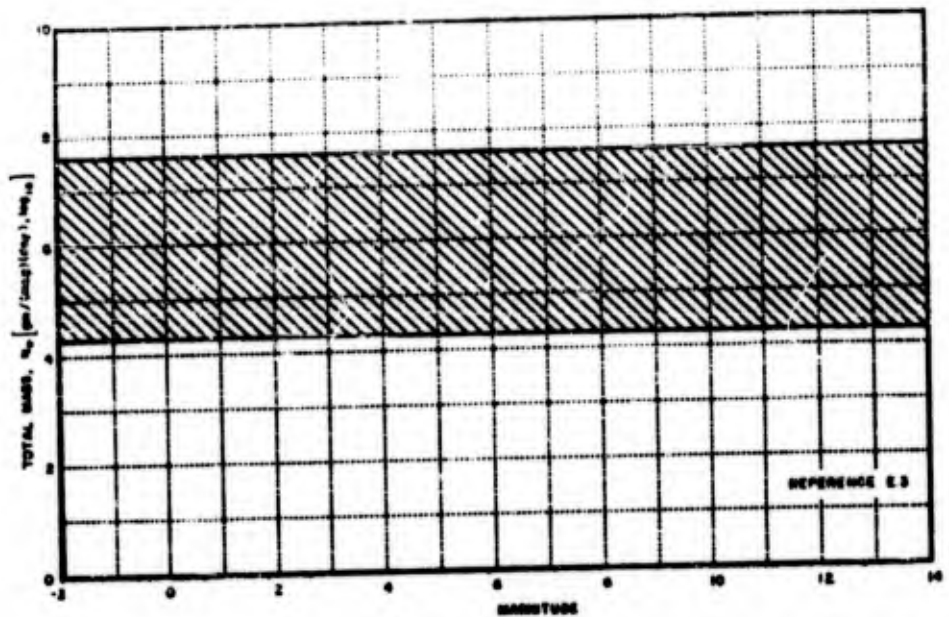


Figure 23. Total Meteorite Mass Per Magnitude Encountered by the Earth's Atmosphere

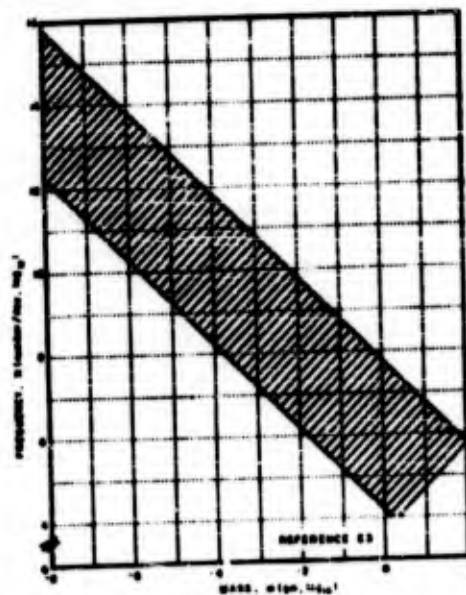


Figure 24. Estimated Mass and Frequency of Meteorite Particles Encountered by the Earth's Atmosphere

Meteorites do not approach the earth from a random direction but are concentrated in the plane of the ecliptic (the earth's orbital plane). This implies that if a space vehicle wishes to avoid the meteorite problem for part of its mission it may be able to do so by positioning itself above or below the plane of the ecliptic.

The probability of a meteorite collision with a space vehicle must currently be deduced from the frequency with which meteors are observed in the earth's atmosphere. The actual frequency may be as much as ten times greater during a meteor shower than that shown in Figure 21. Some known meteor streams are listed in Table 7. The magnitude scale used is the customary astronomical scale in which each step denotes a change in luminous intensity by a factor of 2.5. Very bright objects have negative magnitudes and an increasing positive magnitude denotes decreasing intensity. The upper line in Figure 21 corresponds to an early estimate by Millman based on visual observation and the recent estimate by Whipple based on photographic observations. The lower line corresponds to the estimate of Watson based on visual and telescopic observations, and the estimate of McKinley based on radio observations. It now becomes apparent from the ranges covered by the data that any estimate of meteorite impact and penetration will be crude. A vehicle in close proximity to the earth will be shielded by the earth from meteorite impact. However, this reduction by a factor of two is negligible compared with the other apparent uncertainties.

Table 7
Meteor Streams - Orbital Data¹

Name	Maximum	Geocentric Velocity (km/sec)	Semi-major Axis, a (A.U.)	Eccentricity e	Perihelion, R (A.U.)	Aphelion R (A.U.)	Longitude of		Orbital Inclination to Ecliptic (°)	Associated Comet
							Ascending Node Ω (deg)	Perihelion ω (deg)		
Quadrantids	Jan 3	46	→∞	→1.0	0.9	→∞	282		85	
Lyrids	Apr 21	81		0.986	0.92		30	213	80	1961
Eta Aquarids	May 6	66		0.967	0.969		48	103	102	Halley
Arietids	June 7	37		0.94	0.10		77	29	16	
Zeta Perseids	June 7	27		0.78	0.38		77	61	4	
Beta Taurids	July 1	29		0.86	0.34		278	244	8	
Delta Aquarids	July 28	80	→∞	→1.0	0.04	→∞	308		86	
α Piscis Austrinis	July 28	46	80	0.99	0.9		282		88	
Perseids	Aug 12	61		0.96	0.963		139	168	116	1962 III
Giacobinids	Oct 9	22		0.715	1.0		196	174	31	1933 III
Orionids	Oct 20	67		0.97	0.97		28	143	161	Halley
Taurids	Nov 7	27		0.89	0.33				8	Encke
Leonids	Nov 18	72		0.908	0.98		233	177	163	1866 I
Andromedids	Nov 23	16		0.786	0.889		248	224	13	Biela
Geminids	Dec 12	36.2		0.90	0.14		269	326	34	

¹Note the high geocentric velocity of the meteor streams in retrograde orbits ($i > 90^\circ$).

Estimates of the dust present in space have been derived from various records made on satellites and rockets, studies of zodiacal light and estimates of the amount of dust falling upon the earth. Robertson, Wyatt and Whipple have shown that the relativistic interaction of dust particles with sunlight causes them to spiral slowly into the sun with a radial velocity inversely proportional to their solar distance. Whipple (Reference E2) has shown that the dust spiralling into the sun might be replenished by the comets as they are heated in approaching the sun.

We thus have the picture of a constant flux of dust particles generated by the passage of comets and subsequently drifting into the sun at a rate of several tons per second. The planet's gravitational attraction will cause the dust to approach the plane of the ecliptic with a drift velocity inversely proportional to the square root of the planet's solar distance. Inclusion of this effect causes a dust concentration in the ecliptic plane inversely proportional to the three-halves power of the solar distance.

From solar corona measurements, it is estimated that the particle density at the position of the earth's orbit is between 10^{-14} and 10^{-15} particles cm^{-3} , depending on whether the minimum particle radius is one or ten microns.

The effect of the dust blanket near the earth's surface is to increase the concentration stated above (estimated by calculations which ignored the earth's gravitational field) by a factor possibly as large as 1000, depending on the eccentricity of the dust's orbit. Thus the dust density above the earth's atmosphere may be as great as 10^{-12} particles $\text{cm}^{-2} \text{sec}^{-1}$, a value in good agreement with data received from Explorer III (Reference E1).

Direct measurements of micrometeorites were obtained during the International Geophysical Year by monitoring the impacts of cosmic dust on satellites and deep space probes. The largest data sample resulted from an experiment using crystal transducers to detect impacts upon the exposed sensitive area. The impact rate on Explorer 1 (1958 Alpha) was 8.0×10^{-7} particles $\text{cm}^{-2} \text{sec}^{-1}$ for cosmic particles of mass greater than 8×10^{-10} g based upon the calibration and an impact velocity of 30 km/sec (Reference A24). The density of cosmic material in space at one astronomical unit (AU) is 5×10^{-22} g cm^{-3} for this component of cosmic dust, or approximately 10^{-20} g cm^{-3} based upon a mass distribution assumption. The density of cosmic material measured from Pioneer 1 is less by more than an order of magnitude than that measured on Alpha 1958; the impact rate was 4.0×10^{-7} particles $\text{cm}^{-2} \text{sec}^{-1}$ for particles of mass greater than 10^{-10} grams for similar impact conditions.

Effects

When a solid particle impinges upon a surface, the energy is dissipated in the form of radiation, ionization, evaporation, melting, heating and physical displacement of the material. The important effects that may result from this impact of meteorites, micrometeorites or dust with the vehicle's surface are: penetration, noise and erosion.

Penetration. The lack of both a theoretical model and experimental data has made the task of evaluating the damage due to condensed matter in space a difficult one. Various formulae for meteorite impact have been proposed but thus far the only points of agreement are, the penetration depth is proportional to the characteristic dimension and the penetration depth to characteristic dimension ratio is proportional to some constant power of the velocity.

The value of this velocity exponent is very much in dispute. Whipple (Reference E3) favors the two-thirds power while Pugh and Eichelburger favor the one-third power. Both of these values are suggested by the same argument: namely, the craters maintain similar geometry for specified target and projectile but are affected by impact velocity. If the crater volume is proportional to the kinetic energy of the projectile then the two-thirds power pertains. If, on the other hand, the crater volume is proportional to the momentum of the projectile then the one-third power is obtained. Huth, et al, (Reference E3) arrived at the 1.4 power by postulating that the penetration to characteristic dimension ratio was a function of "impact Mach Number". Bjork and Gazley (Reference E3) found the following formula to be adequate.

$$\frac{P}{D} = \frac{\text{Penetration Depth}}{\text{Characteristic Dimension}} = 1.169 V^{0.315} \quad (19)$$

This equation applies to any projectile of any shape as long as one dimension of the projectile does not greatly exceed that of another (see Figure 25 for a comparison of these various postulated relationships).

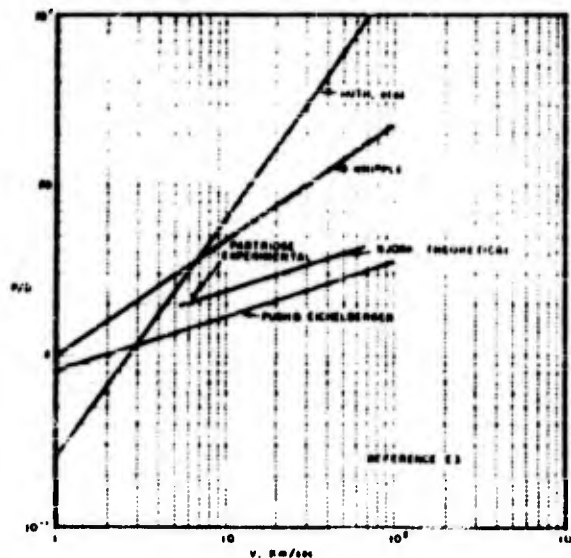


Figure 25. Penetration Laws for Iron Spheres Striking Thick Iron Targets

From Equation (19) and the data presented in the preceding section on Environment, Bjork and Gazley derived the plot shown in Figure 26 which gives the flux of meteorites penetrating a distance P into steel.

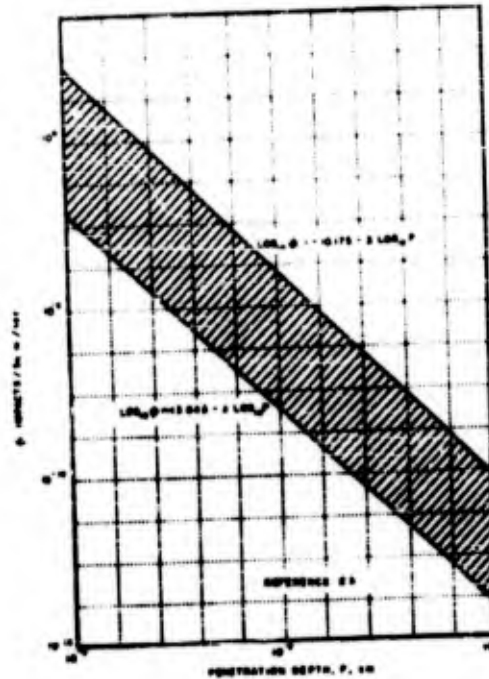


Figure 26. Flux of Meteorites Penetrating to Depth P or Greater

An empirical formula that applies to all materials is (Reference E19):

$$N_h = \frac{\delta}{Nh^3} \left(\frac{E}{E_0} \right)^{0.27} \quad (20)$$

where

- N_h = number of punctures per hour for 10m^2 of exposed area
- h = thickness of hull
- E = modulus of elasticity of hull material, psi
- E_0 = reference modulus, 10^6 psi

The above is for a solid hull wall and does not apply to a double hull where the outer hull serves as a meteorite bumper. Theoretically the bumper would shatter the hypervelocity particle, so that the material sprays out from the hole in the bumper and covers a large area on the main or inner hull. This loss in concentration of energy permits thin hulls to be used, so that a saving in total weight is effected.

A comparison of the thicknesses required for an aluminum structure with that required for a steel structure for the same impenetrability is shown in Figure 27.

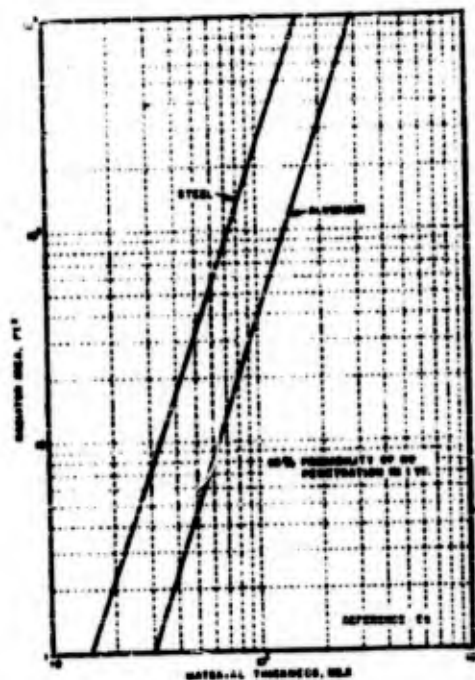


Figure 27. Meteorite Shielding Requirements

A specific example will illustrate the probability of both a penetration and a decompression of the internal chamber. The chamber is a cylinder whose diameter and length are each six feet. The skin thickness is 0.1 cm (1 millimeter) of steel and the internal pressure is 7.0 psia. From Figure 26, on the average the chamber will be penetrated once in the period ranging from 6 days to 35 years depending upon which boundary of the graph is chosen. This discloses nothing regarding the resulting hole size.

For the chamber to decompress to a fatal pressure level in ten minutes or less would require a hole at least 0.6 cm in diameter. The probability that a meteorite of sufficient size and kinetic energy to cause a hole this large will be encountered is at most once every 100 days. Therefore the

probability of a cabin decompression resulting in a very short time from a meteorite penetration is extremely small and for short duration missions almost negligible.

A problem much more serious than decompression is that of a slow leak resulting from penetration. A meteorite penetration of pipes carrying a working fluid would probably be difficult both to find and to repair and could, therefore, create some malfunction which might cause excessive discomfort or death to the astronaut. Similarly, a cabin penetration would cause an excess leakage of the atmosphere, thus shortening the mission.

The figures quoted thus far have been in terms of the average meteorite activity. At certain intervals, the earth passes through what are commonly designated as meteor streams (see Table 7, page 54). Some of these streams are regular and can be predicted. Presently, it is not known what streams, other than those that cross the earth's orbit, will be encountered in space. The probability of penetration during one of these streams is increased at least seven and probably ten times over that estimated for the average meteorite flux.

Noise. The noise produced by meteorite or micrometeorite impact may be important. Estimates of the noise produced are unreliable because of the lack of a theoretical model or experimental data. The noise produced could be either helpful or harmful to the astronaut. The lack of sufficient background noise, if the machinery is isolated from the astronaut, could conceivably cause the development of abnormal emotional reactions to the noise produced by condensed matter because of the disturbed balance between sensory input and intra-nervous activity. It is also conceivable that the noise, if frequent enough, could produce an opposite effect by producing a background noise level, although the likelihood of this event is not too probable. The noise may further aid the astronaut by providing him with an acoustical indication where an impact has occurred thus aiding him in locating a possible puncture.

Erosion. The minute dust particles are of no significance in causing punctures of the vehicle skin but they may erode the surface and thus change the vehicle's optical properties. Momentum and shock considerations, which usually dominate most hypervelocity problems, are totally irrelevant when considering hypervelocity impact of dust particles because the amount of momentum energy released per unit area is too small by far to inaugurate a shock wave or to produce any other momentum effect.

Thus the problem becomes that of the individual ion. Approximately 10^{11} dust atoms will be involved in and statistical or temperature considerations will dominate the process (Reference E3). The total energy delivered will be of the order of 100 ergs, which is very small, but the energy per dust atom is relatively large, being in the neighborhood of 10 eV. The duration of impact is about 10^{-9} seconds and therefore the power delivered is very high being about 10^{28} eV cm⁻² sec⁻¹ although the pulse is too rapidly

attenuated to make it significant. The heat produced is lost by sonic or thermal transport in the solid, by radiation or evaporation from the surface, or by decomposition of the vaporizing target or dust compounds.

Thus dust erosion should significantly alter the optical properties of a vehicle's surface in a period of from one to ten years with the latter figure probably the more reasonable. Estimates made by Whipple (Reference E18) and others have indicated that the combination of all erosive effects will significantly alter the optical properties of a vehicle in space in a period of about one year. Structurally this erosive action is of no significance since altering the optical properties requires surface erosion only to a depth of $\lambda/2\pi$ [where λ is the radiation wavelength of interest ($\sim 4000 \text{ \AA}$)] or less than 0.1μ .

Primary Malfunctions

Condensed matter in space may result in any number of malfunctions depending on the vehicle design. Some of these are:

1. Penetration with the resultant penetrating particles having sufficient energy to do internal damage such as:
 - a. subsystem destruction,
 - b. decompression or increased atmospheric leakage,
 - c. possible direct damage to the human.
2. Erosion destroying the optical properties of the vehicle's external surface resulting in:
 - a. abnormal load on temperature regulation system resulting in abnormal cabin temperatures.
3. Structural degradation of vehicle due to either framework weakening or some other means.

Aspects Requiring Simulation

The effects and possible malfunctions that may occur due to condensed matter are many. The particular vehicle design chosen will determine many and consequently we can speak only in generalities here. The general areas requiring simulation are:

1. Penetration resulting in decompression or an increase in the atmospheric leakage rate
2. Noise produced by impacting particles
3. Any damage to the vehicle's structure or subsystems that may result

4. Any effects that may result from the erosive damage to the vehicle's surface

ADEQUACY OF EXISTING DATA

Most of the data presently available on the condensed matter that exists in space was acquired or extrapolated from the visual phenomena associated with meteors entering the earth's atmosphere. Depending on the method used to interpret this data, a wide range of values have been given, all having a high degree of uncertainty. It is therefore desired that:

1. Direct measurement by satellites and/or space probes be made of the size, mass, velocity and frequency of impact.
2. Direct measurement be made of the erosive properties of the smaller particles (dust) that exist in space.

Some earth-bound laboratory work is also desired in the area of the effects of hypervelocity impact on structural materials and on measuring the noise produced from such impacts.

SPATIAL FORCE FIELDS

Many investigators have theorized that spatial fields do exist in inter-planetary space. Verification of these theories must await measurements from future space probes. Pioneer IV encountered no solar plasmas but preliminary measurements from Pioneer V have indicated the existence of a gigantic magnetic field whose axis bears no relation to that of the sun.

GRAVITATIONAL, MAGNETIC AND ELECTROSTATIC FIELDS

Environment

Strictly speaking, a discussion of space environment must include the gravitational field. This field is a composite of an almost uniform galactic field, insofar as our solar system is concerned, and that field determined by the position and mass of the various bodies within the solar system. The laws governing the gravitational field within the solar system have been developed and therefore, if not already done, the gravitational field at any time can be calculated for any point in space. Unless extreme accuracy were required the gravitational forces exerted on a vehicle in the near vicinity of the earth-moon system would be determined by the masses and positions of the earth, moon, and sun with respect to the vehicle.

The earth's magnetic field in space can be likened to a magnetic dipole at the earth's center, oriented along a line from the center of the earth to a point near latitude 78.6°N and longitude 70.1°W on the earth's surface. The magnetic moment of this dipole is about 8.1×10^{25} electromagnetic units (emu) and has been decreasing slowly with time although some believe that it is now increasing.

At points beyond the earth's atmosphere at a distance a (where a is in earth radii) from its center, the magnetic field falls off very nearly as a^2 , or in terms of the surface value of about 0.5 gauss, is given by $0.5/a^2$. Recent measurements by Pioneer V indicate the earth's magnetic field is measurable occasionally as far out as 14 earth radii.

Other measurements received from Pioneer V show evidence of a steady magnetic field that makes a large angle with the plane of the earth's orbit. Further data on this phenomenon and its source should be available in the near future.

The Sun too has a magnetic field with a surface strength close to that of the earth. Within the sunspots, it becomes much greater. Portions of the magnetic field of the sunspots can be expected to be carried by the material within the streaming corona to the neighborhood of the earth-moon system with measurable intensity. Sunspot fields are thus expected to exist in a fragmentary but highly disorganized form within the solar system.

Many investigators have speculated that blobs of solar ionized gas, with dimensions varying from a few to many thousands of kilometers and carrying magnetic fields, at times fill a good deal of space as far out as the planet Jupiter. The blobs may carry fields in excess of the galactic field of near 10^{-6} gauss and probably approach or may even exceed 10^{-4} gauss.

Presently, no data is available on the electrostatic fields that may exist in space. Their strengths, however, will probably not be large enough to be significant.

Effects

The gravitational field and the vehicle's thrust vector will determine the trajectory. However, the former is not directly perceivable to the space crew, except insofar as it is opposed by vehicle thrust or external physical constraints such as air drag or reaction by planetary surfaces. The magnitudes of the magnetic and electrostatic fields in space, as measured or speculated on, are such that no direct vehicular effects of significance can be attributed to these phenomena.

ADEQUACY OF EXISTING DATA

Pioneer V has thus far supplied most of the data on force fields in space other than those measured directly at the earth's surface. These fields are of interest, but their magnitude is probably so small that they present no great problem to manned space flight in the near vicinity of the earth-moon system. Therefore even though the data have applications for interplanetary flight, it is believed that the lack of data will have no serious consequences on manned space flight in the near future.

UPPER ATMOSPHERE

This discussion is only concerned with the thermosphere and lower exosphere regions. Measurements of the physical properties of these regions have been made but most of these were taken by high altitude rockets and were, consequently, of short duration. Recently additional data have been derived from the orbits of earth satellites and these studies have revealed many discrepancies in the original conclusions drawn from the rocket data.

THERMOSPHERE* AND EXOSPHERE**

The earth's atmosphere from an altitude of about 80 km to the neighborhood of 1000 km is of interest here. The auroral phenomenon, usually centered around 100 km, is excluded since it was discussed earlier.

Environment

The physical characteristics of the upper atmosphere are discussed under the following subheadings: Density, Temperature, Ionization and Winds.

Density. The subject of major interest is the variations of atmospheric density that may occur. Density values used in specific model atmospheres are compared with the density values inferred from the orbit of the satellite 1958 ϵ in Figure 28. The data points are somewhat scattered but for the most part, especially when one considers the low densities involved, the model atmospheric density versus altitude as estimated from the orbits of satellites 1957 α through 1959 ζ (Sputnik I through Discoverer VI).

The densities plotted from satellite data in Figures 28 and 29 refer to the latitudes between 70°N and 50°S and to all seasons. No sign of any systematic variation of density with latitude or season has yet been found although scattered rocket data show that at 200 km above Fort Churchill (59° 45'N, 94°00'W) the summer daytime atmospheric density is 6.6×10^{-7} g m⁻³ which is twice the winter daytime value. In view of the small scatter

*"Thermosphere" is defined as the region between the mesopause (altitude ~ 60 km) and the "exosphere" or outer fringe of the atmosphere.

**The "exosphere" is the region lying above the critical level where the average distance a horizontally moving gas-particle travels before colliding with another gas-particle equals a certain specified fraction (usually ~ 0.5) of the local decimal scale height.

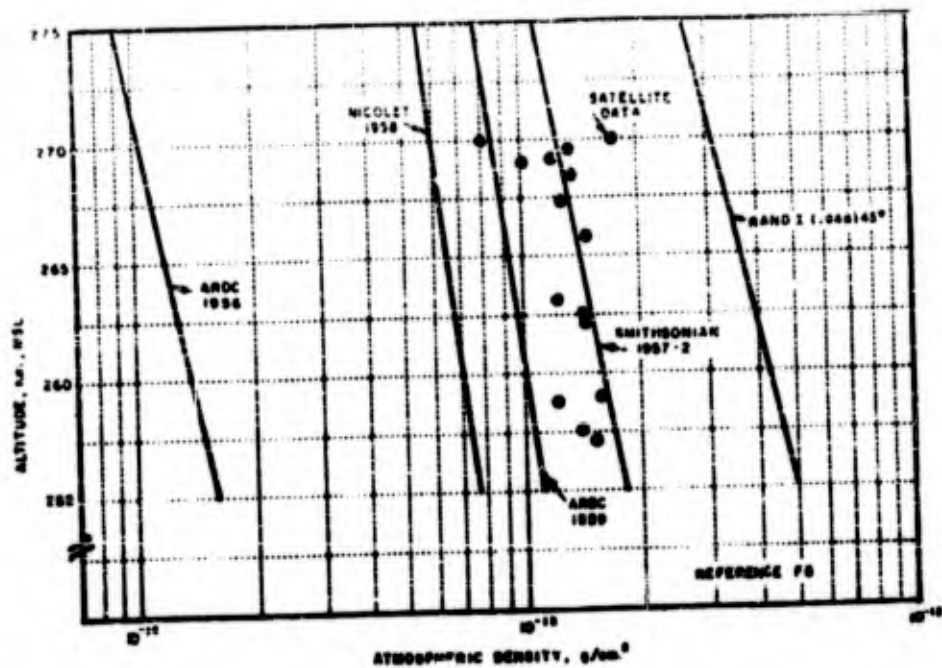


Figure 28. Atmospheric Densities Derived from Satellite 1958 Epsilon (Portions of Model Atmospheres are Included for Comparison)

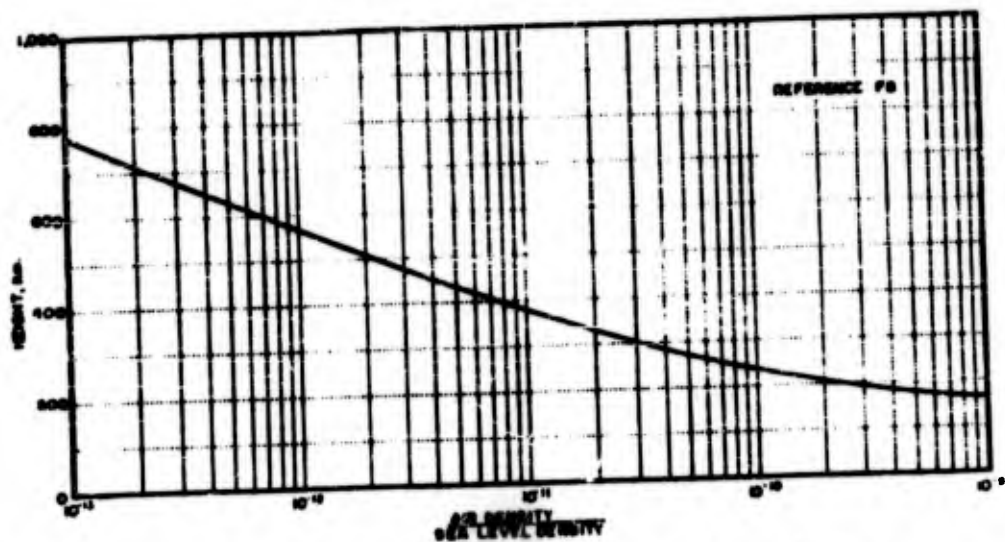


Figure 29. Air Density from Satellites 1957 Alpha to 1959 Zeta

found in satellite data below 300 km, it seems reasonable that the density does not depart from its average by a factor of more than 2 and probably 1.5 as a result of latitude variation (between 70°N and 50°S) and with season.

Some doubt is given to this conclusion, however, by the finding that at the summer daytime density 200 km above Fort Churchill was as measured by high-altitude rockets, five times the corresponding density over White Sands, New Mexico. Other rocket measurements have shown wider variations by as much as a factor of 10. Further investigation is required.

On successive days during November 1958, densities inferred differed from the average by +2%, +11%, -1%, and +18%. The peak values of density and also the minimum values, show a strong tendency to recur at intervals of about 28 days. The influence of the sun seems to be the major cause of this cycle. It appears the atmospheric density at heights between 100 and 500 miles is strongly influenced by solar activity. Appreciable day-to-day irregularities have been observed which may or may not be due to solar activity.

Analysis of the orbital data of Sputnik III has disclosed the strong possibility of a day-night variation in density at altitudes near 220 km. The information available is so meager that any estimate of the magnitude of this variation is of doubtful reliability.

Temperature. The "temperature" of gases and particles in the upper atmosphere and outer space is the average kinetic energy per particle. Only in the lower atmosphere is this also equivalent to the equilibrium temperature that can be established between atmospheric gases and a thermometer. Plots of average temperature conditions as a function of latitudes and altitude have been published (References F6 and F17). In general, between 30 and 150 kilometers, there are only small variations between daytime and nighttime temperatures. Above 200 kilometers, rather large diurnal variations do occur.

Ionization. The ionosphere was once believed to consist of a number of distinct layers each with its own specific ionization characteristics. Recent measurements taken by instruments borne in high-altitude rockets have disclosed this to be untrue, at least during the daylight hours. Superimposed upon the continuum of ionization through the layers are occasional very high ionization gradients.

Above Fort Churchill (58° 45'N, 94° 00'W) it was found that as the altitude increased from 100 km to 150 km to 200 km the order of relative abundance of positive ions during the daytime changes from (O_2^+ , NO^+) to (NO^+ , O_2^+ , O^+) to (O^+ , NO^+ , O_2^+); during the night the NO^+ is the most prevalent in the lower altitudes. Data on the altitudes greater than 250 kilometers is scarce but data collected by Sputnik III indicates the principal ion is O^+ with a small percentage of N^+ . This information indicates that the atmosphere above 250 kilometers is probably entirely atomic in nature (see Figure 30).

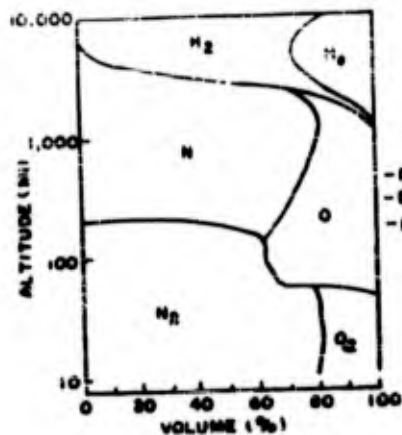


Figure 30. Approximate Composition of the Atmosphere

The D-region, the lower 25 km of the ionosphere, is the most important region within the ionosphere. The electron densities in this region are relatively low compared to the other regions and vary only some thirty-fold from the normal value. The energy-dissipating factor, electron collision frequency, is quite large and may vary as much as a hundred-fold in magnitude. This variability is generally the most dominant characteristic of the D-region. The average electrical conductivity is relatively low being only 10^{-4} times that of sea-water. However, it varies through a range of 10^{10} depending on the frequency. The dielectric "constant" is nearly constant but develops negative values at the upper edge of the region.

Winds. Various means have been used to measure winds at altitudes up to 400 km. One method of measuring winds which has been used extensively for the altitudes between 80 and 100 km is the measurement of the drift of meteor trails. Between 80 and 100 km the average prevailing winds for all months are predominantly in the east-west direction. During the summer and winter these winds exhibit large vertical velocity gradients. The outstanding feature of these gradients is the large and opposite wind gradients that exist in the east-west direction during December and July and the almost complete absence of the gradients during September and March. The average wind gradient in December is $+2.3 \text{ m sec}^{-1} \text{ km}^{-1}$ and in June $-3.3 \text{ m sec}^{-1} \text{ km}^{-1}$. The annual variation of the north-south component of the prevailing wind is much smaller but more regular than the east-west component. The maximum speeds increase with height from approximately $\pm 5 \text{ m sec}^{-1}$ near 80 km to $\pm 20 \text{ m sec}^{-1}$ at 100 km.

Periodic components of the winds in the 80-100 km region have both 24-hour and 12-hour periods. The amplitude of the diurnal component is approximately independent of height but does exhibit large annual variations. Maximum wind speed of $40\text{-}50 \text{ m sec}^{-1}$ occur in the summer and autumn and minimum speeds of $20\text{-}30 \text{ m sec}^{-1}$ in the winter and spring. The phase of the

diurnal variation varies monthly but between 75 and 94 km there is a tendency for the wind to be directed north at about 1800 hr. during the summer, autumn and spring while the phase of weak oscillations during the winter is opposite. Between 95 and 104 km the behavior of the 24-hour component is irregular with regard to both sense of rotation and phase.

In comparison to the diurnal component, the 12-hour oscillation behaves in a very complex manner. During the month of June, the amplitude gradient is near $2.5 \text{ m sec}^{-1} \text{ km}^{-1}$ while in December it is almost zero. The phase varies irregularly from month to month.

Only scattered data and inconclusive results are available for altitudes above 104 km. A plot of the summer and winter wind components expected in the atmosphere to an altitude of 350 km is presented in Figure 31. The components shown were determined from latitudinal temperature gradients adopted for the various layers in 1955.

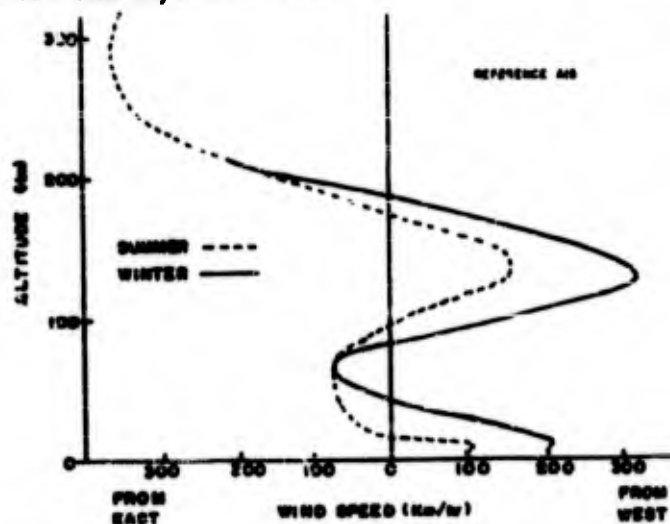


Figure 31. Estimated Mean Summer and Winter Wind Components

Effects

The characteristics of the upper atmosphere indicate that besides the aerothermodynamic effects normally associated with re-entry only one other non-negligible effect may appear; namely, communication interference. The variations in the atmospheric parameters from the mean values customarily presented in model atmospheres are not usually of sufficient magnitude to cause any significant unaccounted for effects on the vehicle.

Aerothermodynamic Effects. Numerous papers and articles have been presented the past few years that discuss the effects associated with re-entry through the earth's atmosphere. These aerothermodynamic effects associated with re-entry depend on the vehicle's configuration and its trajectory. Any discussion of these effects would be very lengthy and since the information is widely available no further discussion is presented here.

Communication Interference. For long paths within the ionosphere, especially in the D-region, certain unfavorable orientations of the signal wavefronts with the geomagnetic field can lead to an extremely high signal loss. At frequencies above 100 mc/s, these effects should disappear but even at 100 mc/s, wave amplitudes may occasionally be reduced ten and even a hundred-fold on a geophysically disturbed day.

An unusual aspect of the D-region is with respect to the possible signal interference from terrestrial sources. Above the ionosphere, the radio frequency spectrum below one mc/s, which is normally quite crowded and noisy on earth, should be relatively clear of terrestrial signals. This should be especially true for terrestrial interference sources in the portions of the earth in sunlight where there is a D-region. Signal sources in the shadow portions should also generally be of insignificant strength although some signal leakage via magneto-ionic ducting may occur.

Aspects Requiring Simulation

Besides aerothermodynamic effects, which were not included in the discussion, the only other aspect of the upper atmosphere requiring simulation is the possible loss of communications while within the ionosphere.

ADEQUACY OF EXISTING DATA

The lower regions of the upper atmosphere have been rather extensively studied and any additional data would only refine that already available. At satellite altitudes the reverse is true, comparable density, temperature, ionization and wind data being relatively meager. However, at these altitudes, the short duration effects are negligible, and consequently the inadequacy of data did not seriously affect the study.

SUMMARY OF ASPECTS REQUIRING SIMULATION

Until recent years, man's quest for knowledge of the space environment has been entirely from an earthbound posture. Consequently any environmental phenomenon that could not penetrate to this region went unnoticed or was estimated by theoretical induction from other data. The last few years have seen the development of unmanned satellites and space probes enabling direct measurements of the characteristics of the environment, although not always to the accuracy desired. It is encouraging to note that over-all a good deal is known about the space environment. However, many specialized phenomena are still very roughly understood and concerning some, the available information is entirely inadequate for even a fair understanding of the consequences to manned space flight.

Consequently the conclusions stated here are subject to review as new data become available.

This section briefly summarizes the aspects of the environment found during the study that require simulation for the purpose of training a space crew.

The preceding sections indicated that the environmental factors that created the most important effects requiring simulation were (in approximate order of importance):

- . Corpuscular Radiation
- . Electromagnetic Radiation
- . Condensed Matter
- . Gaseous Medium
- . Spatial Force Fields

It would be convenient to say all the environmental factors of space, their effects and any resulting malfunctions should be simulated. However, in simulation, it is important to realize that the main interest is duplicating the effects of the environment rather than the environment per se. Thus all the environmental factors, their effects, etc. would not be included in the simulation because the contribution from many to the simulation would be negligible. Only the more important effects would be included.

The upper atmosphere was not included in this section because the fluctuations from the mean values presently envisioned would not contribute any effects detrimental to the man-machine system.

CORPUSCULAR RADIATION

Recent physical measurements indicate there are two regions that cause concern:

The radiation intensities within the Great Radiation Belt.

The intense radiation resulting from certain solar flares.

Because of the heavy nuclei present, cosmic rays may cause some concern.

The space vehicle has designated areas or provides vestments to protect the crew during periods the vehicle is operating under one of the above conditions. The radiation environment, because of its effects on the human, will need to be simulated passively, e. g., a meter reading the present dose rate and integrated dose within the space cabin, and the emergency procedures to be taken should also be simulated. Further, if it is determined that for the particular vehicle being simulated these two regions of concern will cause either transient or permanent malfunctions to occur, these too must be simulated.

ELECTROMAGNETIC RADIATION

The EM radiation in space, along with the optical properties of the vehicle's surface, will ultimately effect the internal heat balance either by a fluctuating temperature or a fluctuating load on the temperature control equipment. The vehicle will be designed to operate with an almost constant internal temperature ($70 \pm 10^\circ \text{F}$), but in the event the active temperature regulation (or mechanical passive) equipment should malfunction, the resulting fluctuation in internal temperature should be simulated.

The EM radiation in the radio wave region results in a noise input to the communication system. During certain periods of a specific trajectory, this noise (depending on the direction in which the antenna is directed, solar activity, etc.) may interfere with communications at times, making the received signal completely unintelligible.

CONDENSED MATTER

A puncture of the vehicle's skin can result in innumerable malfunctions which will not all occur as the result of the same penetration. These include:

- . Decompression of the penetrated compartment
- . An increase in the atmosphere leakage rate
- . Malfunction of a subsystem
- . Injury to the crew

Repair procedures will be specified for the malfunctions that may occur and, along with the malfunction, should be included in the simulation.

Erosion of the vehicle's surface will, given sufficient time, alter the vehicle's optical properties and also alter the characteristics of optical systems, e.g., windows, lenses, etc. The alteration of the optical properties of the surface will change the heat balance within the vehicle and, depending on the temperature control system used, may present problems requiring simulation.

GASEOUS MEDIUM

Except for the erosive effects mentioned in the previous paragraph, no other simulation is required.

SPATIAL FORCE FIELDS

The gravitational field is inseparably tied to considerations of propulsion and the resulting vehicle trajectory.

The absence of relative acceleration or force constraints within the space vehicle, unless provided artificially by spinning or accelerating the vehicle, will cause a condition known as weightlessness to exist. Weightlessness is not presently amenable to simulation. Experimental data have indicated that, over short exposure periods, weightlessness does not result in any performance degradation of the individual and, if a solid reference is provided, he readily accommodates to the situation. Prolonged weightlessness may effect the circulatory, nervous, digestive, and muscle systems, but thus far no experimental verification has been obtained.

The magnitude of the effects resulting from other spatial force fields are expected to be insignificant and hence not in need of simulation.

FACTORS RESULTING FROM THE SPACE ENVIRONMENT

The confinement and isolation of a man to a space cabin may lead, depending on the time involved, to major psychological problems. Laboratory simulation cannot simulate the anxiety and fear that arise from being sealed in a small space with the knowledge that if trouble develops, no outside aid will be immediately forthcoming. Consequently, the simulation is not complete, but many of the effects that will result make the simulation well worth the effort.

RECOMMENDATIONS FOR EXTENSION OF THIS STUDY

The information presented in this report forms a preliminary definition of the environmental factors considered necessary to include in a simulation program designed to train space crews. The problem of how to simulate and exactly what specific simulation requirements are necessary still remains unanswered. Therefore, to indicate some of the problems still to be faced and to present brief programs aimed toward the solution of some of these, the following recommendations are made.

DETAILED ENVIRONMENT UNDER GENERIC SPACE MISSION CATEGORIES

1. Select a number of representative missions for manned space systems. These might include:
 - a. Permanent earth satellite (inclined, intermediate-altitude orbit)
 - b. Lunar approach and return
 - c. Lunar satellite station
 - d. Lunar soft landing and departure
 - e. Earth atmosphere re-entry and landing
 - f. Flight to a near planet
2. Determine, on the basis of completed design studies, the specific vehicle configurations most appropriate for each of the missions selected in Part 1. In some cases alternative configurations may be indicated, for example, an interplanetary mission, in both high and low-level thrust configuration should be considered.
3. Generate specific time histories of the exterior and interior environment for the selected space vehicle-mission combinations. Environmental components contributed by the vehicle (e.g., sound, vibration, outgassing products, etc.) are to be included.
4. Generate a list of malfunctions, having nonnegligible probabilities of occurrence, induced by the environmental components peculiar to outer space. Include with each malfunction estimates of the probability of occurrence, techniques for detection or anticipation, and techniques for correction, repair, or avoidance.

ANALYTICAL REPRESENTATION OF THE ENVIRONMENT COMPONENTS OF OUTER SPACE

Cast the available data on the environmental components of outer space into analytical forms directly applicable to procedures for deriving the interior environment of a space vehicle. For example, expression of the Great Radiation Belt in a form which would enable the computation of time histories of the external and internal radiation levels, plus a final integrated internal

done for a space vehicle traversing this region would be particularly useful. The availability of an analytic description of the space environment would simplify the problems of automatic, computer-controlled training simulation "flights".

SIMULATION DESIGN CONCEPTS

The task of determining what to simulate leads naturally to the question of how to simulate it. Some effort should be placed on simulator design concepts, particularly with respect to the unique aspects brought about by the space environment. This program could be efficiently tied to a second program which deals primarily with the establishment of engineering requirements for training simulators. Two areas need to be investigated:

- The selection of a basic computer to represent the environmental effects, and
- The selection of input-output equipment where the input is the forcing functions and the output are displays, etc. required to produce the desired effects on the crew.

EFFECTS OF INDUCED ENVIRONMENTS AND THEIR IMPORTANCE TO THE SIMULATION OF SPACE VEHICLES

The vehicle itself and, in the event of war, hostile enemy action will induce certain hostile environmental factors that may affect the space vehicle and its crew. A preliminary effort in the form of a literature survey should be undertaken to define the possible induced environmental factors that may occur (e.g., those created by the vehicle, namely outgassing, vibration, noise, etc. and those due to hostile enemy action, such as a nuclear explosion in the vicinity of the vehicle), their effects on the vehicle and its crew, and finally which factors need to be included in a space training simulator.

PSYCHOLOGICAL EFFECTS

A large area of uncertainty, with respect to determination of important factors in simulation for space flight training, involves psychological effects such as task and situation-induced stress, isolation, confinement, and sensory deprivation. Demonstration that one or more of these factors are insignificant would have major implications on the engineering requirements for simulation, e.g., the dimensions of the simulator cabin space could be dissimilar to those of the actual space cabin simulated. A literature survey and, subsequently, an analysis of the available results, are recommended as a first attempt to answer questions such as these.

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APPENDIX

Illustrative Example

AN EARTH SATELLITE IN A CIRCULAR EQUATORIAL ORBIT AT AN ALTITUDE OF 300 MILES

INTRODUCTION

The general effects of the natural environment were discussed in this report without considering the effect of vehicle design and mission profile. In reality the specific vehicle design and its mission profile can conceivably alter significantly many of the conclusions presented in the general study. A particular vehicle on a particular mission is illustrated here.

The analysis is concerned only with the effects that result from the natural space environment and disregards those effects that may result from the vehicle and its characteristics, e.g., equipment noise, radiation from an internal nuclear powerplant, etc., which must be included in a complete analysis. The effects of weightlessness, confinement, isolation and physiological functions are ignored. Further, no discussion will be included on those natural environmental effects that were shown to be neglectable in the general study or where insufficient data are available to determine their significance; these include:

- . . surface changes due to extreme ultraviolet and/or soft X-rays
- . . effects of spatial force fields, and
- . . surface changes due to sublimation of materials exposed to the near vacuum of space

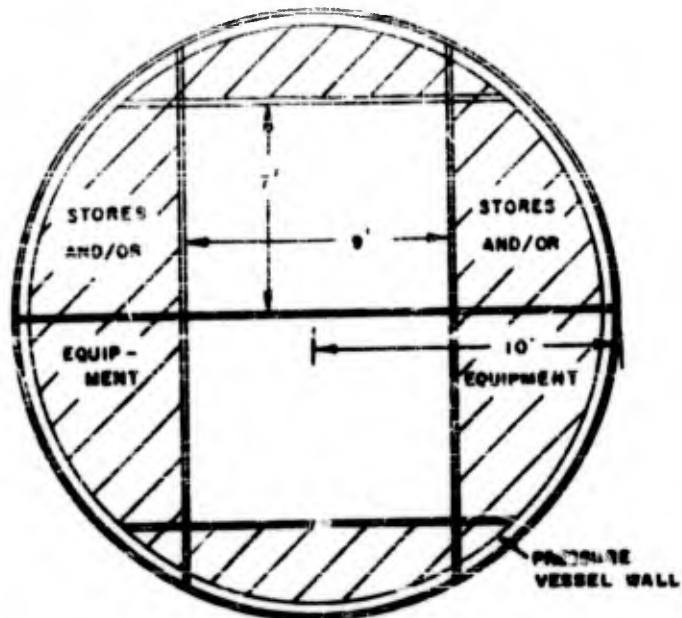
VEHICLE DESIGN

The vehicle is to provide the necessary volume to provide a basic subsistence for a crew of three for a period of three months.

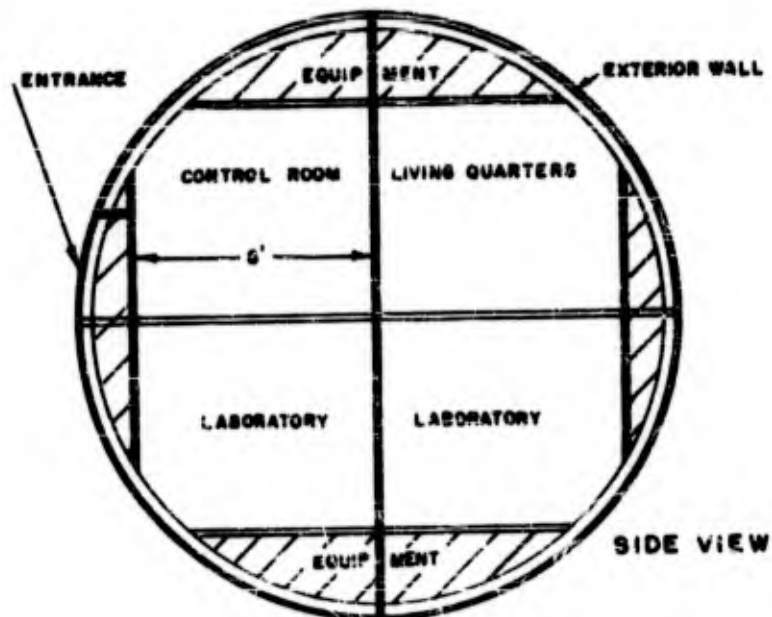
The external configuration of the vehicle is a sphere whose diameter is twenty feet. The external wall supports all structural loads while the sole purpose of the inner wall is to serve as a pressure vessel containing the atmosphere. The interior of the vehicle is subdivided into four sealed compartments, each having approximately 500 cu ft of usable volume (see Figure A1). For cross-sectional view of walls see Figure A2.

MISSION PROFILE

The vehicle orbits the earth in a circular equatorial orbit three hundred miles above the earth's surface. The orbital period is therefore 94.2 minutes of which 58.4 minutes is in direct sunlight and 35.8 minutes is in the earth's shadow.



FRONT VIEW



SIDE VIEW

Figure A1. The Vehicle

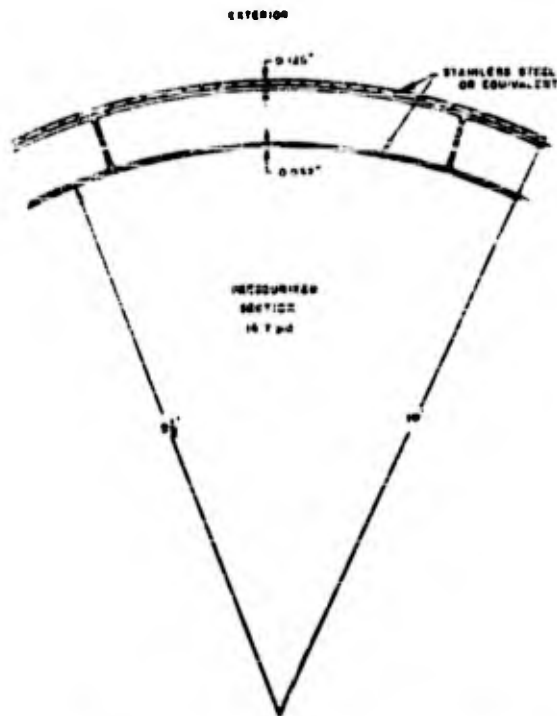


Figure A2. Wall Construction

ENVIRONMENTAL EFFECTS

As in the general study the effects will be discussed under particular subheadings, namely:

- . Electromagnetic Radiation
- . Corpuscular Radiation
- . Gaseous Medium
- . Condensed Matter

The upper atmosphere was excluded because at 300 miles the vehicle is operating in near space conditions and any effects, e.g., deceleration due to atmospheric drag, would not be of sufficient magnitude to affect the crew.

Electromagnetic Radiation

The EM radiation environment existing at an altitude of 300 miles above the earth's surface has two main effects: communication noise and external surface heating.

Communication Noise. The communication system for the satellite must be able to transmit to and receive signals from stations on the earth's surface. Space to space or communication within the satellite will not be of concern in this analysis.

Two principal ranges of frequencies pass readily through the earth's atmosphere. They are: (1) the range between the ionosphere critical frequency and frequencies absorbed by rainfall and gases (about 10 to 10,000 mc/s) and (2) the combined visual and infrared ranges (about 10^6 to 10^9 mc/s). The atmosphere is also partially transparent in a third range below about 300 kc/s.

The range 10 to 10,000 mc/s is the most practical for communication purposes considering the present state of development in radio frequency power generation. The upper limit may be as low as 5000 to 6000 mc/s during heavy rainstorms and the lower limit as high as 80-100 mc/s depending on the degree of solar activity, the location of the earth terminal, and the geometry of the signal path. On the other hand, the window may extend as low as 2 mc/s at polar locations during nighttime periods to as high as 50,000 mc/s at high altitude rain-free locations. But, to be sure the transmitted signal will penetrate the earth's atmosphere the radio communication frequency range from 100 to 5000 mc/s should be used.

The second fundamental limitation on space-earth communication is the noise which tends to mask the transmitted signal. Noise is generated in receiving amplifiers, and noise reaches the receiving antenna from space. Figures A3 and A4 are plots of total noise temperature (sum of receiving amplifier noise and antenna noise) for a low-noise triode receiver and a parametric receiver with antennas directed toward different portions of the surroundings.

The minimum transmitting power required can be calculated from:

$$P_t = \frac{4\pi S_r R^2 L}{G_t A_r} \quad (1)$$

where

P_t = radiated power, watts

S_r = received signal power, watts

G_t = transmitting antenna gain

A_r = effective receiving area of receiving antenna, ft^2

R = range, ft

L = system loss, db

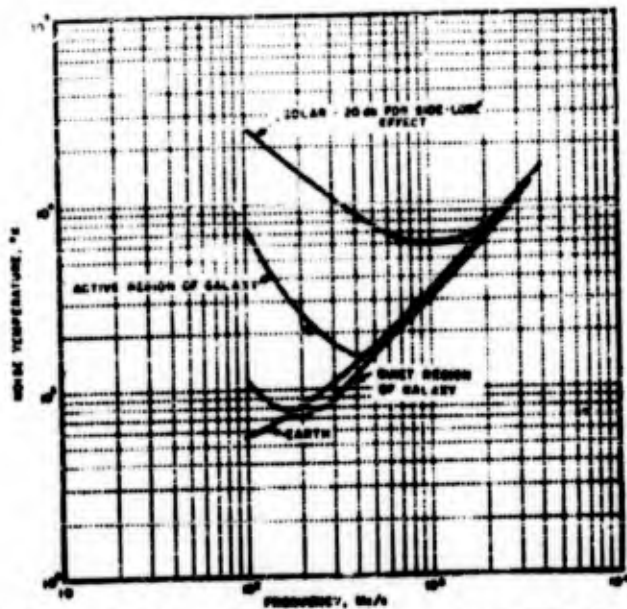


Figure A3. Noise Temperature for Triode Receiver with Antenna Directed Toward Various Sources

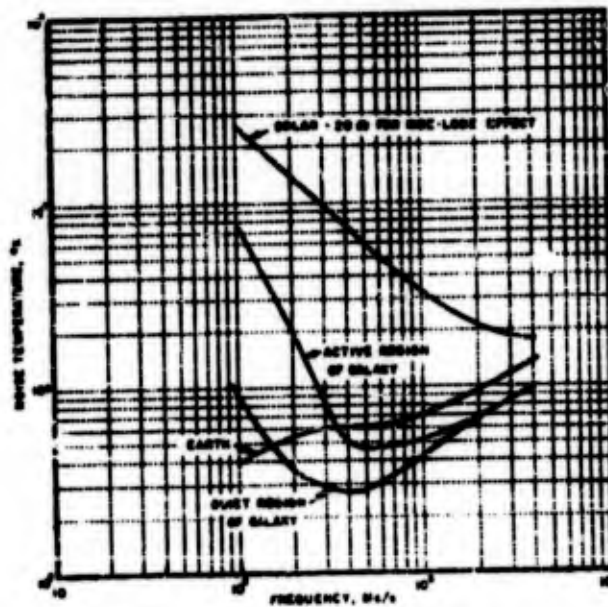


Figure A4. Noise Temperature for Parametric Receiver with Antenna Directed Toward Various Sources

The received signal power can be calculated from

$$S_{r_{min}} = 0.7 N_0 C \quad (2)$$

where

- $S_{r_{min}}$ = minimum received signal power, watts
 C = ideal rate of transmission, bits/sec
 N_0 = noise power density, watts/cps

$$N_0 = \frac{1.38 \times 10^{-23} BT}{f} \quad (3)$$

where

- B = frequency range, cps
 T = noise temperature, °K (for values see Figures A3 and A4)
 f = frequency used, cps

and

$$G_T = \frac{4\pi A_r f^2}{c^2} \quad \text{for a paraboloid antenna} \quad (4)$$

where

- G_T = transmitting antenna gain
 A_r = effective receiving antenna area = 0.7 actual antenna
 c = velocity of light = 1×10^9 ft/sec
 f = frequency, cps

Table A1 presents an estimate of the minimum power required at a frequency of 250 mc/s for a parametric receiver with receiving antenna directed at three sources: earth, sun, and a quiet region of the galaxy. The values in the table were based on:

- C = 10 bits/sec (50 words/minute in English)
 A_r = 700 ft²
 L = 10 db

It should be emphasized that the values shown in Table A1 represent theoretical values subject to the selection of parameters.

Table A1

Minimum Theoretical Values of Average Transmitted Power
for a Frequency of 250 mc/s over a Range of 500 Miles
at a Channel Capacity of 50 words/minute

Noise Source		
Earth	Sun (minus 20 db for side-lobe)	Quiet Galactic Region
7.3×10^{-8} watts	1.3×10^{-6} watts	3.6×10^{-8} watts

In the frequency range presented as practical for space-earth-space communications (100 to 5000 mc/s) the sun may during certain solar noise storms increase the noise power density by as much as a factor of 1000. Consequently during certain periods the signal may be masked completely by solar noise, depending on where the antenna is directed, and therefore communications from the satellite to the earth or vice versa would be impossible.

Surface Heating

Nomenclature

- ϵ = surface emissivity in the infrared region
- σ = Stefan Boltzmann Constant = 5.78×10^{-8} watt meter⁻²·K⁻⁴
- α_v = visual albedo = reflectivity of the vehicle's external surface in the visible region
- T = surface temperature, °K
- E_0 = solar constant = 1400 watts meter⁻²
- P_i = power per unit area of internal wall surface dissipated
watts meter⁻²
- k = height of vehicle above earth's surface, miles
- R_e = earth's radius = 3963.18 miles at the equator
- m = vehicle's mass per unit area, Kg meter⁻²

- C_p = specific heat at constant pressure, joules $^{\circ}\text{K}^{-1} \text{Kg}^{-1}$
 f_{ET} = eclipse factor (accounts for the fact during one period the vehicle is shielded from the sun by the earth for a portion of the orbit)
 α = angle at which the vehicle enters the earth's shadow, degrees
 ζ = angle between the vehicle orbit and the sun, degrees
 i_F = angle between the sun and the equatorial plane, degrees
 Ω = distance along the equator between the sunlit node (point at which the orbit crosses the equator) and local noon
 α_e = earth's albedo ≈ 0.34
 q = heat transferred, watts
 A = surface area, meter²

Subscripts

- 1 outer surface of pressure vessel wall
 2 inner face of outer wall

The major sources of heat input to the vehicle's external surface are: (1) direct sunlight, (2) reflected sunlight and thermal radiation from the earth, and (3) power dissipated internally. Cosmic ray heating and the heat input resulting from collisions with condensed matter are estimated to be less than 10^{-6} watt m^{-2} and 2×10^{-5} watt m^{-2} respectively; negligible quantities when compared with the above three sources. Calculations based on Oppenheim's generalized theory of convective heating in free-molecule flow and on recent atmospheric density data has disclosed that for mean altitudes greater than 200 miles aerodynamic heating averaged over the entire surface of a three-dimensional body is small enough to be neglected.

The energy received by the vehicle will be transferred primarily by radiation. Therefore the temperature attained by the vehicle's surface is primarily a function of its radiation characteristics in the infrared and visible regions and of the thermal properties of the vehicle itself. The heat conductivity of the vehicle is considered to be so perfect that all portions of the external surface are at the same temperature.

The equations* expressing the surface temperature are:

Cyclic Equilibrium Temperature

$$T_s = \left[\frac{(1 - \alpha_r) E_0 \left(\mu_T + \frac{\alpha_E}{T} \cos \xi \right) + \epsilon (188.5) + P_i}{4\epsilon\sigma} \right]^{1/4} \text{ } ^\circ\text{K} \quad (5)$$

where

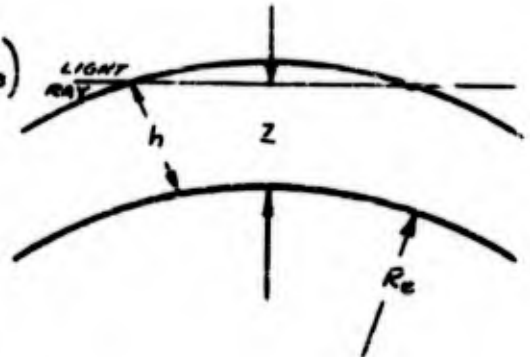
$$\sin \xi = \sin(i_s + \tan^{-1} \frac{\sin \Omega}{\cot i_s}) \left(1 \cos^2 \Omega \sin^2 i_s \right)$$

$$\Omega = \cos^{-1} \frac{R_E + Z}{R_E + h}$$

$$\mu_T = 1 \text{ for } x > 90 - \xi$$

$$\mu_T = \frac{90 + x}{180} \text{ for } x < 90 - \xi$$

$$x = \cos^{-1} \frac{R_E}{R_E + h}$$



Maximum Temperature (always in sunlight)

$$T_{max} = \left[\frac{(1 - \alpha_r) 1400 \left(1 + \frac{\alpha_E}{T} \cos \xi \right) + \epsilon (188.5) + P_i}{4\epsilon\sigma} \right]^{1/4} \text{ } ^\circ\text{K} \quad (6)$$

Minimum Temperature (always in shadow)

$$T_{min} = \left[\frac{\epsilon (175.2) + P_i}{4\epsilon\sigma} \right]^{1/4} \text{ } ^\circ\text{K} \quad (7)$$

*For derivation of these equations see: Goldman, D. T. and Singer, S. F. "Studies of a Minimum Orbital Unmanned Satellite of the Earth, Part IV Radiation Equilibrium and Temperature", Proceedings of the VIth International Astronautical Congress, 1956

Nonequilibrium Conditions

$$t = \frac{mC_p}{4\sigma^{\frac{1}{4}}P^{\frac{3}{4}}} \left[\log \left\{ \frac{P^{\frac{1}{4}} - \sigma^{\frac{1}{4}}T}{P^{\frac{1}{4}} + \sigma^{\frac{1}{4}}T} \right\} + 2 \tan^{-1} \frac{\sigma^{\frac{1}{4}}T}{P^{\frac{1}{4}}} + C \right] \quad (8)$$

where

$$\sigma = 460^\circ$$

P = total power input at time t by all sources, watt/m²

C = constant of integration determined from initial conditions

t = time in seconds

The power per unit area dissipated internally to the surface, P_i , is assumed to be 57 watts per square meter.

Figure A5 shows the effect the absorptivity to emissivity ratio has on the maximum temperature attainable by the vehicle's surface if always exposed to the sunlight. Figure A6 shows the effect of emissivity on the minimum surface temperature attainable if the vehicle remains in the earth's shadow. From these two extremes and some known surface properties a value of 0.6 for the surface emissivity and 1.33 for the absorptivity to emissivity ratio was selected.



Figure A5. Variation of Maximum Surface Temperature with Absorptivity to Emissivity Ratio

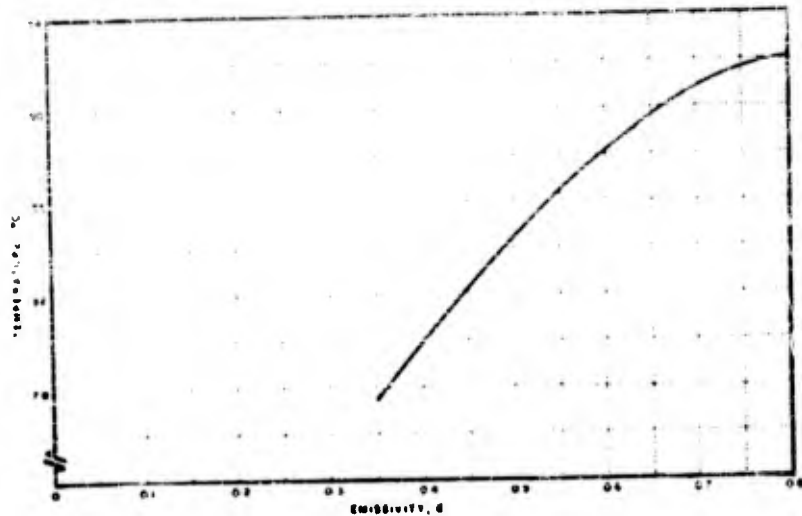


Figure A6. Variation of Minimum Surface Temperature with Emissivity

Using these values for the surface characteristics and an initial vehicle surface temperature of 300°K the resulting nonequilibrium temperature profile for the vehicle was calculated from Equation 8. The results are shown in Figures A7 and A8.

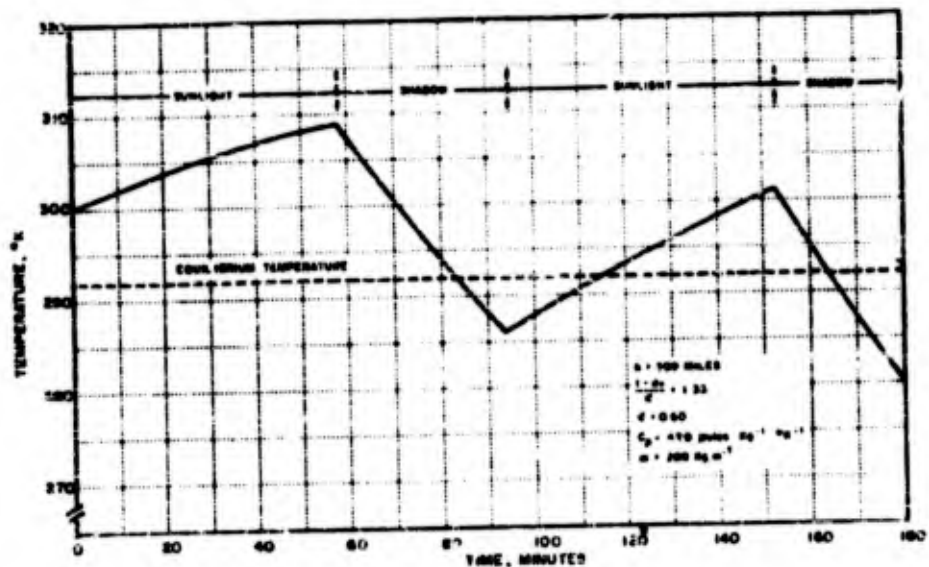


Figure A7. External Surface Temperature for First Two Initial Orbits

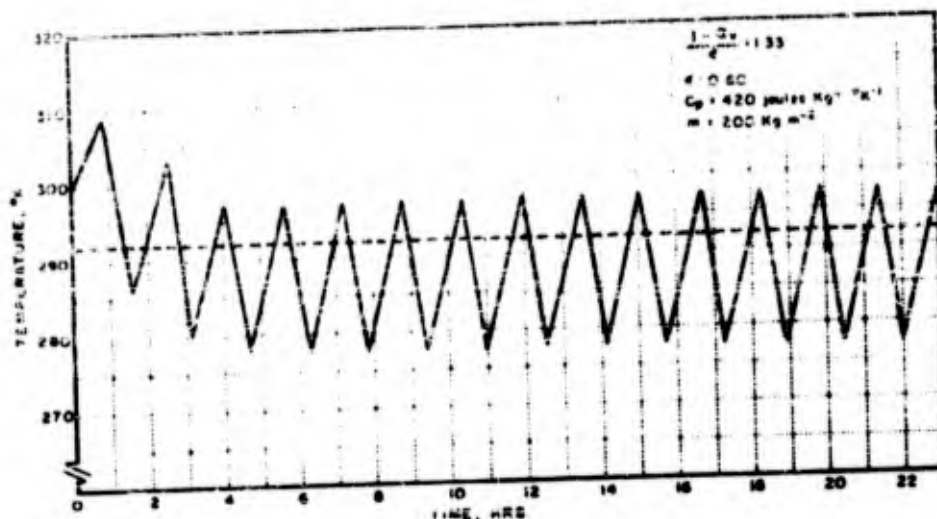


Figure A8. External Surface Temperature of the Vehicle While in Orbit at 300 Miles Above the Earth's Surface

It should be noted that these results pertain only to a spherical vehicle with the parameter values indicated on each figure and do not hold for all cases. The use of different characteristics may have resulted in less temperature variation and possibly an equilibrium temperature more suitable, resulting in a better passive temperature control system than that used in this example.

The temperature extremes inside the crew compartment will be determined by the capability of the structure to transfer the heat produced within the vehicle. Two estimates of the range of internal temperature extremes will be made; the first estimate is based on an assumption that all the heat is transferred by radiation and the second is based on an assumption that all the heat is transferred by conduction. Both estimates are crude, since (1) the actual transfer process will be some combination of the two and (2) both calculations find the cabin wall temperature and, because the conditions are transient, the internal atmosphere will usually not be in equilibrium with the cabin wall.

The heat transferred from the inner wall to the outer by radiation alone can be expressed analytically as:

$$q = \frac{A\sigma(T_1^4 - T_2^4)}{\left(\frac{1}{\epsilon_1} + \frac{A_1}{A_2}\right)\left(\frac{1}{\epsilon_2} - 1\right)} \quad (9)$$

A cross section of the wall is shown in Figure A2. Assuming an emissivity of 0.4 for each wall surface the following temperature extremes are found for a \dot{q}_f equivalent to 57 watts per square meter of external surface:

maximum inner wall temperature 149°F
 minimum inner wall temperature 124°F

The heat transferred by conduction assuming the walls are united at all points can be expressed analytically as:

$$q = 8\pi kr(T_1 - T_2) \quad (10)$$

Using the value of k for steel and again a \dot{q}_f of 57 watts per square meter of external surface area the temperature extremes are found to be:

maximum inner wall temperature 80°F
 minimum inner wall temperature 44°F

The two estimates are crude but to improve them by using a combination of radiation and conduction would require a more thorough knowledge of the structural properties of the vehicle plus a complicated computer program beyond the scope of this report. The actual temperature extremes would thus lie somewhere in the range of 44 to 149°F.

A more sophisticated passive control system, one that employs a relatively simple mechanism to adjust a number of reflecting and absorbing screens, or recourse to an active system, refrigerating and heating devices, could keep the interior of the vehicle at the almost constant temperature ($70 \pm 10^\circ\text{F}$) required by the crew. However, the initial program of temperature control would have to be automatically or manually revised every few months because the optical properties of the surfaces exposed to the space environment may be altered significantly in a time period of the order of one year.

CORPUSCULAR RADIATION

At 300 miles above the earth's surface the vehicle is below the inner zone of the Great Radiation Belt. The estimated unshielded radiation dose (as measured by Explorer IV) during conditions of a "quiescent" sun is approximately 9 roentgens per year. The conversion factor presently recommended for converting ionization dosages (rep)* to biological dosages

*roentgen equivalent physical (rep) - the quantity of ionizing radiation which will produce 1.6×10^{12} ion pairs per gram of human tissue, or the amount of ionizing radiation that is capable of releasing the same energy in tissue as one roentgen of X or gamma rays.

(rem)* is one for electrons and 4 for protons (Reference A23). Assuming the worst condition, i.e., the composition is 100% protons, the maximum unshielded dose is in the neighborhood of 36 rem/year or 9 rem/quarter. Present AEC limits are 3 rems per 13 consecutive weeks whole body radiation if the exposure affects critical organs and 6 rem/quarter if no critical organs are involved, provided the age-pro-rated allowance of 5 rems annually after the age of 18 is not exceeded (Reference C13).

Occasionally, solar flares cause a sudden increase in cosmic ray intensity. However, since the vehicle's trajectory is a circular equatorial orbit at an altitude of 300 miles, its mission is entirely within the region designated the "storm cellar". This region lies below the inner zone of the Great Radiation Belt and due to the magnetic cutoff of the earth's dipole field, the protons emitted by the sun during these periods cannot penetrate into the region. Consequently, the radiation intensity within the storm cellar seemingly does not fluctuate significantly and can be assumed to be always equal to the normal cosmic ray intensity at that altitude.

If the orbit had been inclined sufficiently to cause the vehicle to leave the storm cellar (latitudes $\geq 40^\circ$), at least one compartment would require shielding sufficient to attenuate the expected radiation to a tolerable level. Since the vehicle in question is not on an inclined orbit and energy levels of the particles composing this radiation have not been resolved to a degree sufficient for estimating shield weights, no estimate will be attempted for an inclined orbit.

A well-designed vehicle structure will provide some shielding tending to reduce the conservative estimate cited above. Consequently, the need for mass shielding over and above that provided by the structure is, if necessary, minimal and certainly if required could be incorporated without imposing a too severe weight penalty.

GASEOUS MEDIUM

The gaseous medium will contribute toward eroding the surface of the vehicle and therefore, after a sufficient length of time, alter the vehicle's optical properties. Two factors will contribute to this, namely, sublimation due to the vehicle existing in an almost perfect vacuum, and atomic and molecular sputtering. The available data on the significance of the sublimation of alloy materials are not sufficient to allow conclusions to be presented. Atomic and molecular sputtering will be discussed from a theoretical standpoint.

*roentgen equivalent man (rem) - that quantity of radiation (of any type) which, when absorbed by man, produces an effect equivalent to that produced by the absorption of one roentgen of X or gamma radiation.

At 300 miles there are in the neighborhood of 10^6 particles per cubic centimeter. This means the vehicle will be struck by nearly 1.2×10^{19} particles per square centimeter of surface area per year. If for every particle that strikes the vehicle one atom is sputtered from the surface then about 1×10^{-4} cm or 1 micron, μ , of surface material will be removed per year. If the temperature control is passive and the external surface is an evaporated gold or oxide layer the removal of one micron of material could seriously effect the vehicle and its occupants. Because of the extremes quoted here it seems very unlikely that the vehicle's surface properties will be significantly altered in less than one year by sputtering alone.

CONDENSED MATTER

The primary effects of condensed matter in space with which this example are concerned are: (1) erosion of the external surface, and (2) penetration of the vehicle. Other effects, including the noise produced when a particle of condensed matter impinges upon the vehicle's surface, will be disregarded either because of inadequate data or theoretical means of understanding the effects.

Erosion

In order that optical erosion become significant the surface must be roughened to at least an average depth of the order of $\lambda/2\pi$, where λ is the wavelength of interest. Whipple (Reference E18) estimates that for a surface density of 3 g cm^{-3} the maximum rate of erosion will be $1.5 \times 10^{-13} \text{ cm/sec}$. Therefore, for $\lambda = 5000 \text{ \AA}$ the time required to change the optical properties significantly will be about 1.7 years.

Corpuscular radiation from the sun, mostly protons moving at velocities up to 3000 km/sec or more, may contribute another $2 \times 10^{-13} \text{ g cm}^{-2} \text{ sec}$. The effect of this corpuscular erosion, sublimation and other minor erosive effects is to decrease the expected optical lifetime from the 1.7 years for meteorites alone to the neighborhood of one year.

Penetration

Based on the best statistical data available, the maximum number of particles penetrating to a depth P , $0 < P \leq 1 \text{ cm}$, can be expressed analytically as (Reference E3):

$$\log_{10} \phi = -10.175 - 3 \log_{10} P \quad (11)$$

and the minimum number as:

$$\log_{10} \phi = -12.345 - 3 \log_{10} P \quad (12)$$

where

ϕ = impacts/square meter/sec

P = penetration depth, cm

The vehicle is of double wall construction (see Figure A2) with the outer wall, exclusive of the mass shielding for particulate radiation on one of the cabins, being 0.32 cm and the inner wall 0.08 cm. (These thicknesses were estimated based on the outer wall being the structural wall while the inner wall serves as a spherical pressure vessel with a pressure differential of 14.7 psi. Both walls were considered to be stainless steel or some equivalent material.)

Using Equations 11 and 12 and a vehicle surface area of 117 meter.² it is found that the outer skin will be penetrated once, statistically, in the range of every 5 days to 62 years. If it is assumed the outer and inner walls act as one wall whose thickness is 0.40 cm then statistically the inner wall will be penetrated once every 10 days to 122 years.

The figures cited above do not indicate the resulting hole size. Bjork (Reference E3) (see Figure 25) calculated the penetration-to-characteristic dimension ratio for the velocities of interest and found it to lie somewhere between 2 and 4.

Each sealed cabin has approximately 500 cu ft of air space and from Figure A9 for the cabin to decompress to a fatal pressure level in ten minutes requires a hole whose diameter is 0.5 inch (1.27 cm). If the minimum penetration to characteristic dimension ratio, $P/D = 2$, is used then the particle must have the ability to penetrate at least 2.54 cm. From Figure A10 it is estimated that statistically this event will occur once in 520 days (for a $P/D = 4$ the event will occur once in 8550 days). Both of these estimates are probably conservative. Because of the uncertainty of the statistical probabilities of penetration the effect of the earth shielding the vehicle has not been accounted for, if it were, the times quoted above would be doubled. Therefore statistically a penetration resulting in decompression within ten minutes would occur once every 1.4 to 23 years (2.8 to 46 years if the earth's shielding effect is accounted for). The discrepancy in the ranges of time occurrence (e.g., a penetration will occur once in the range of 10 days to 122 years while a penetration resulting in a compartment decompression in ten minutes or less will occur once in the range of 1.4 to 23 years) is the result of using Bjork's results for the former and the curve plotted from data by Whipple for the latter (see Figure A10).

A decompression time to a fatal pressure level in ten minutes is relatively slow and consequently would enable the crew to take corrective action, such as dress in a pressure suit, enter another compartment or repair the leak. For decompression to occur in 2.5 minutes the statistical measure of occurrence is at most once every 23 years. One should bear in mind that all of these times are average periods between occurrences. The natural periods encountered will fluctuate considerably from the average. Further, the encounter of meteor streams by the vehicle will result in a statistical increase

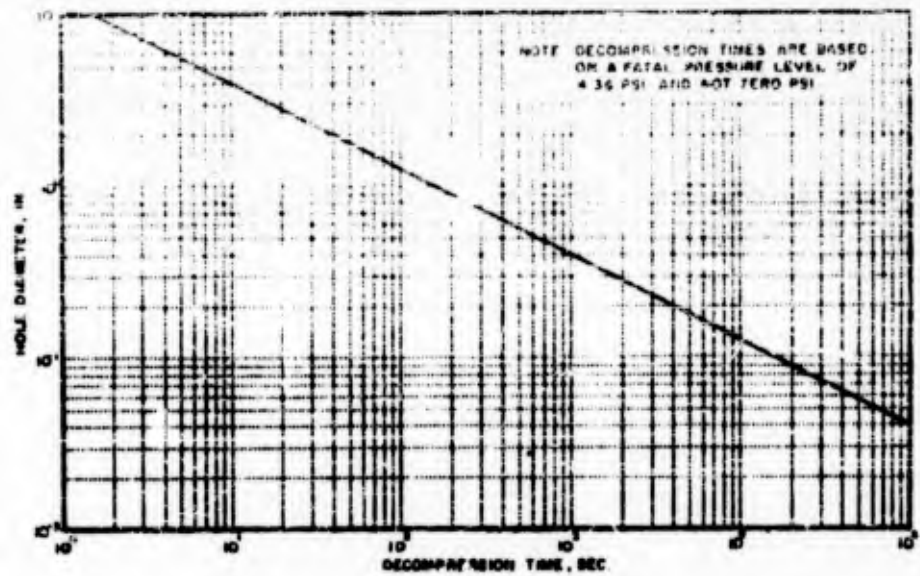


Figure A9. Decompression Times vs. Hole Diameter for a 500 cu ft Sealed Cabin at a Pressure Differential of 14.7 psi

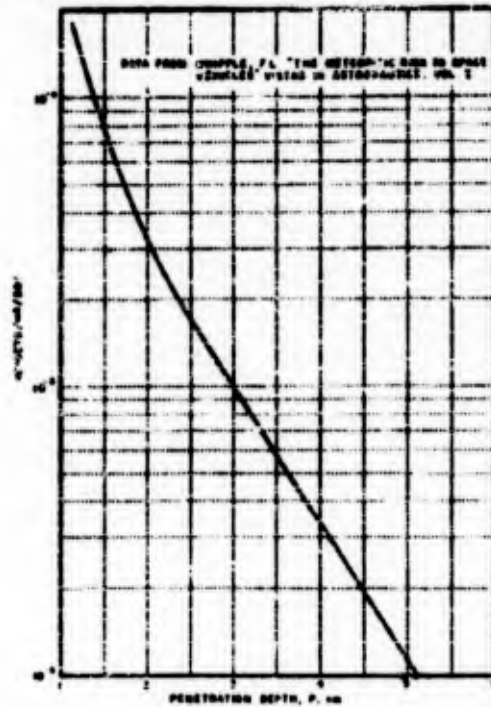


Figure A10. Penetration of Stainless Steel by Meteorites for $P > 1$ cm

of these average occurrence periods by as much as a factor of ten during the period of encounter. Consequently, decompression due to a meteorite penetration is an unlikely occurrence, nevertheless it is a problem that cannot be overlooked.

MALFUNCTIONS

The example as presented included very few vehicle design details; consequently, only a few probable general malfunctions can be listed and these will not be discussed in great detail.

Studies of space system reliability have revealed that it is not the hostile environment of space per se, but the over-all reliability of the well-designed space vehicular system, especially the complex space cabin system, which will determine the success and safety of an orbital mission. The over-all reliability of a system equals the produce of the reliability of the independent components, namely:

$$R_s = (R_1)(R_2) \cdots \cdots (R_n) \quad (13)$$

Therefore, even if the number of critical components could be reduced to 100, each 99.9% reliable, the mission would end in failure one out of ten times. Mission duration will also effect the system reliability as the probability of failure must be a monotonically increasing function of time.

Besides those malfunctions resulting from the unreliability of components (which in general can be expressed statistically) the following environment caused malfunctions may occur:

1. Penetration of vehicle by condensed matter resulting in:
 - a. an increased atmospheric leakage rate or possibly the slow decompression of one compartment,
 - b. disruption in output of, or destruction of one of the critical components such as:
 - (1) vehicle power supply
 - (2) ventilation equipment
 - (3) guidance equipment
2. Surface erosion (a long-term effect which will take at least one year after the vehicle is placed in orbit to become significant) resulting in:
 - a. abnormal loads on temperature control system.

PARAMETERS NEEDING SIMULATION

Without going into great detail the preceding analysis indicates there are parameters that should be included in a training simulation program for the particular vehicle and mission selected. The corrective action to be taken in each case can be done many ways and consequently will not be included in the discussion.

Those parameters considered necessary to include in a simulation program are:

1. Malfunctions in the control of the internal atmosphere
 - a. temperature increase or fluctuations,
 - b. decrease in rate of atmosphere regeneration,
 - c. increase in humidity, etc.
2. Penetration of sealed cabin
 - a. slow decompression, $t > 2.5$ min
 - b. increase in the atmospheric leakage rate resulting not in a serious pressure drop but in too rapid a depletion of reserve atmosphere
3. Interruption of communications correlated with solar activity and satellite position.
4. Radiation dose rate and integral dose

SUMMARY

The preceding example indicated some of the effects that vehicle design and mission profile may have on the environmental parameters to be simulated in a space training simulator. Today, good engineering design practices will enable a vehicle to be designed that provides the crew with a habitat not far removed from that presently experienced by an earth-bound caged animal. The psychological and physiological problems encountered (due to weightlessness, confinement, isolation, etc.) may be far more serious than the problems induced by such parameters as condensed matter, radiation, etc.

For the circular equatorial orbit 300 miles above the earth's surface and for the vehicle in question, it was disclosed that the probability of a catastrophic event, i.e., decompression occurring from a meteorite penetration, was very small but nevertheless such a possibility could not be ignored. Because the vehicle's mission is entirely within the region designated the storm cellar, the vehicle should not experience radiation intensities other than the normal cosmic ray intensity for that region. The vehicle has been designed to attenuate this level to a tolerable radiation intensity internally for both crew and equipment. However, due to the uncertainty in present

knowledge and because minimum shielding, i.e., the required structure, was used, for crew safety the internal radiation level should be monitored. The only other natural occurrence that may interfere with the mission is communication noise correlated with solar activity, which by redirecting the antenna or some other countermeasure, probably can be circumvented.

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