INFLUENCE OF A DETAILED MODEL OF MAN ON PROTON DEPTH/DOSE CALCULATIONS

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Abstract

The U.S. Air Force and NASA have jointly sponsored the development of a detailed radiation shielding model of man. This model will be used to plan manned space missions in which especially sensitive human tissues could be subjected to excessive radiation. The model has two configurations -- standing and seated. More than 2500 individual elemental volumes have been used to depict the external conformation, skeleton, and principal organs. The model is briefly described and several examples of its application to mission planning are given.

Introduction

During the past decade, manned space flight has progressed from its beginning as a modern adventure, albeit with considerable supporting technology on the ground, to today's maturity. Even a flight to the moon seems rather routine to the casual observer. Future manned missions will exploit our current capability into the areas of space transportation systems, space stations, and eventually, interplanetary expeditions.

On past manned space programs -- Mercury, Gemini, and Apollo -- the flights have entailed very small radiation doses to the crews. These flights have evolved slowly from exposures to space radiation measured in minutes, to hours, and, finally, days. The next U.S. manned program, Skylab, will be launched in 1973. This precursor of larger space stations will be occupied at first for 28 days; later it will be revisited for 56 days. Much longer occupancy of permanent space stations and interplanetary vehicles will be necessary. Therefore, the astronauts of the future will encounter considerably more radiation than in previous manned space operations.

It is possible that especially radiation-sensitive organs, such as the lenses of the eyes, the gonads, or the blood-forming centers, could receive doses near or even beyond the threshold of permanent damage. Concern for this possibility has led the Air Force and NASA to jointly sponsor the development of a Computerized Anatomical Model Man, which provides the means for computing, with considerable precision, the amount of radiation from space that might penetrate to any specified location in the body.

Description of the Computerized Anatomical Model Man

The requirements for the model of man were as follows:

1) Two configurations, standing and seated;
2) Exterior conformation and dimensions corresponding to the 50th percentile Air Force man;
3) Interior detail, including skeleton and organs;
4) Accuracy - Weight within 10% of the 50th Percentile Air Force man, locations and conformation within 0.1 inch;
5) Computer compatibility - Modified Elemental Volume Dose Program (MEVDP) for the CDC 6000-series digital computer;
6) Five hundred to 1000 elemental volumes, selected from seven types of geometrical shapes incorporated in MEVDP.

The Air Force Weapons Laboratory technical monitor provided a bibliography of anatomical data and the information required for the model to interface with the MEVDP at the start of the study. These data were supplemented by literature searches, consultation with medical authorities, and observation of living subjects, cadavers, and anatomical models.

The three principal phases of model development included organizing the anatomical data from all sources into master views and sectional drawings of the 50th percentile Air Force man, transferring this information into the punched card formats required by MEVDP, and verifying that the resulting computer model was consistent with the drawings.

The first phase was accomplished by a professional artist working in consultation with medical doctors. All drawings are in a common coordinate system, half scale on a ½-inch grid. The external conformation is based on 132 standard measurements obtained during a statistical survey of over 4000 Air Force flight personnel by Hertzberg, Daniels, and Churchill.[1] Unfortunately, no statistical survey has ever been made of human skeletons and organs, especially of Air Force flight personnel. Therefore, the artist and medical consultants referred to models of the human skeleton and organs, and an assortment of human bones to proportion the interior details of the model. Over 100 scaled drawings were made during this phase of the study. Figure 1, showing the skeleton within the outline of the standing man, is a reproduction of one of these drawings.

The next phase of the study entailed transferring dimensions from the drawings, along with the composition and density of the pertinent tissues, onto punched cards in the formats required by MEVDP.[2] The seven geometrical shapes incorporated in MEVDP are shown in figure 2. Even with embedding, it was necessary to use many more elemental volumes than planned at start of the study to achieve the desired accuracy.

Finally, the model was checked -- visually by using a computer graphics option of MEVDP, and

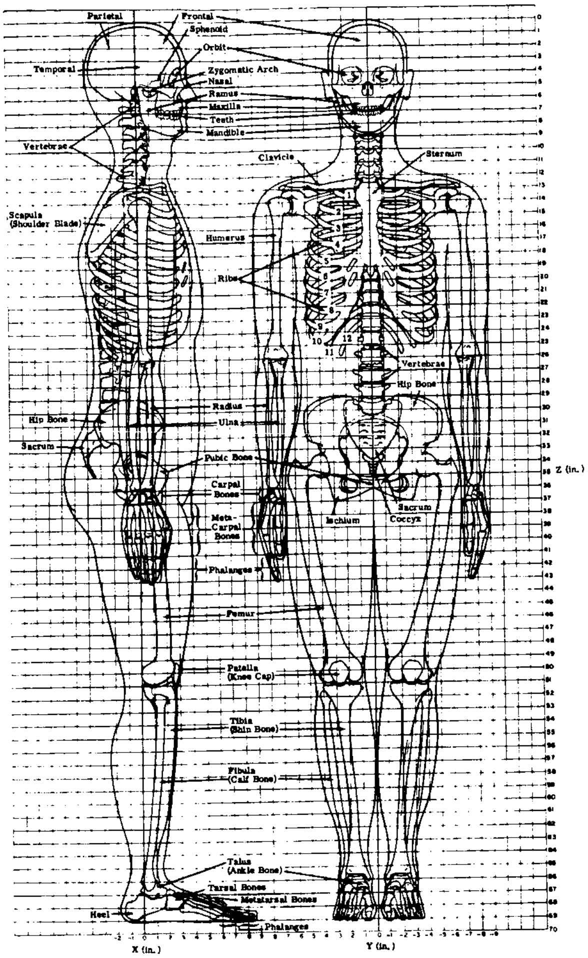


FIGURE 1.-Skeleton within standing man.

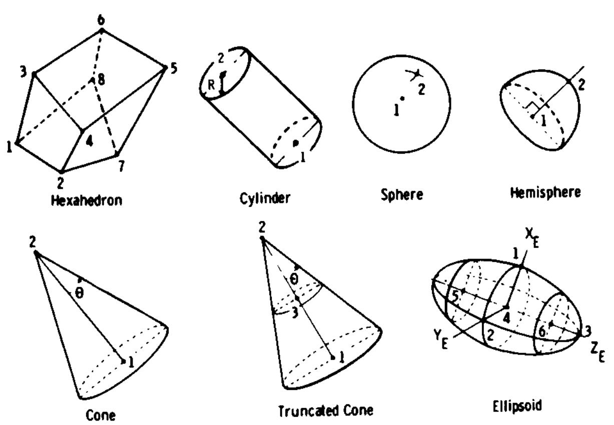


FIGURE 2.-Geometrical shapes compatible with MEVDP.

operationally on CDC and Univac computers at the Air Force Weapons Laboratory and the NASA Manned Spacecraft Center, respectively. A vertical section of the head prepared by the computer graphics option of MEVDP is compared with a sectional drawing prepared by the artist in figure 3. The agreement between the two is very good.

Chemical Composition and Density

The five chemical compositions and densities used in the model are listed in table I. The composition and density of the Radiation Standard Man due to Morgan[3] is shown for comparison as material number 6. Because of insufficient data on the specific composition of human tissues, the model falls short of its objectives in this area. However, refinements of these parameters may readily be incorporated.

TABLE 1.-Materials of the computerized anatomical model man.

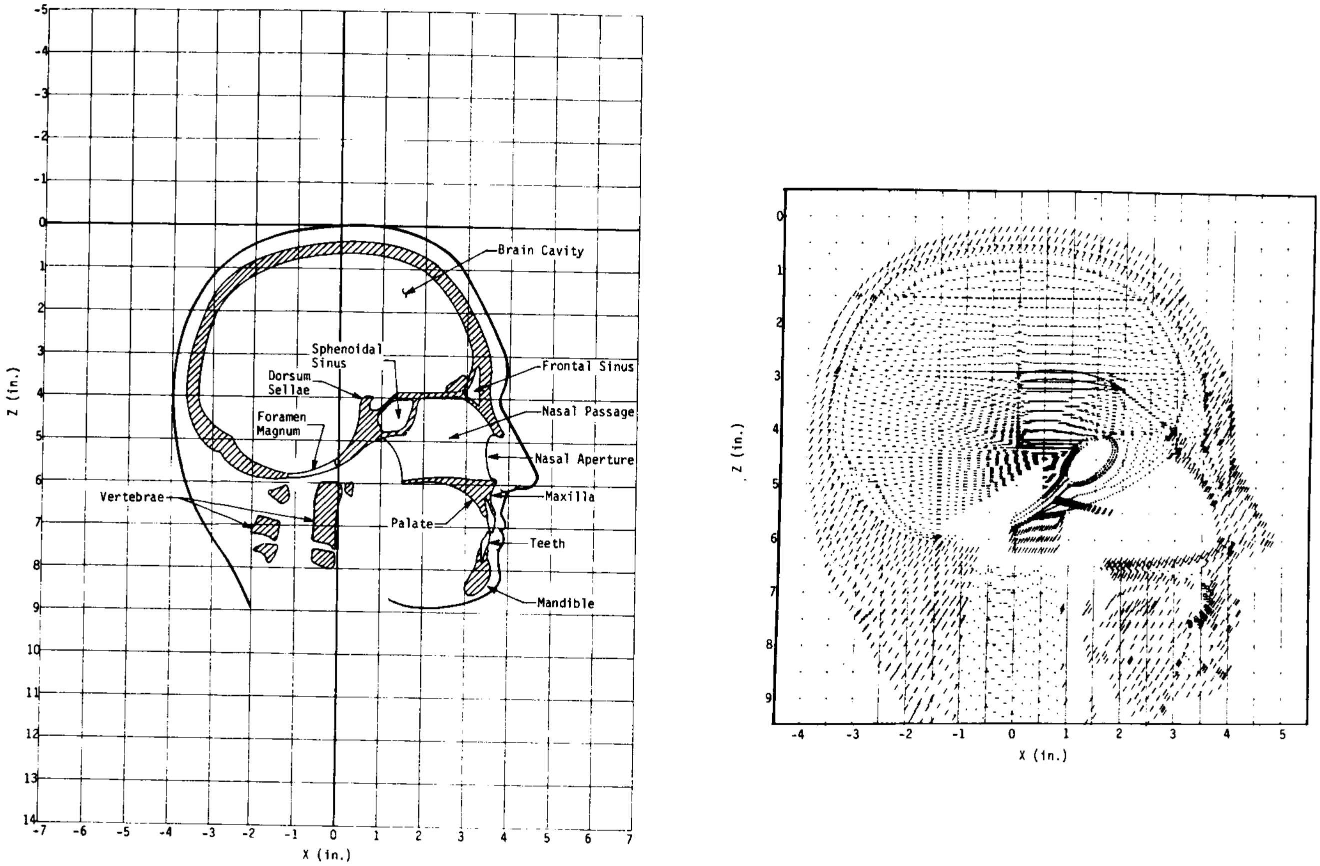
Chemical Element	Fractional Composition by Weight					
	Material Number					
	1	2	3	4	5	6
	Name					
	Lung	Organ	Intestine	Muscle	Skeleton	Radiation Standard Man
	Density (gm/cm³)					
	0.257	1.058	0.451	1.060	1.499	1.000
Hydrogen (H)		0.0980		0.1020	0.082	0.1000
Carbon (C)		0.1450		0.1230	0.423	0.1800
Nitrogen (N)		0.0380		0.0350	0.019	0.0300
Oxygen (O)		0.7070		0.7290	0.322	0.6500
Sodium (Na)		0.0015		0.0008	---	0.0015
Magnesium (Mg)		0.0002		0.0002	0.001	0.0005
Phosphorous (P)		0.0030		0.0020	0.049	0.0100
Sulfur (S)		0.0018		0.0050	0.001	0.0025
Potassium (K)		0.0026		0.0030	---	0.0020
Calcium (Ca)		0.0009			0.103	0.0015
Chlorine (Cl)		0.0020				0.0015

Geometrical Conformation

The model is actually in three sections -- the portion common to both the standing and seated configurations, and portions unique to the standing and seated configurations. These latter portions are combined with the common portion to obtain the complete configurations. The distribution of the nearly 3200 elemental volumes contained in all three portions is shown in table 2.

TABLE 2.-Distribution of elemental volumes in the computerized anatomical model man.

Body Region	Composite Shields	Individual Geometrical Shapes
Common to Both Standing and Seated Configurations:		
Head	153	772
Torso	171	803
Upper Limbs	12	58
Subtotal	336	1633
Unique to Standing Configuration:		
Genitals	9	27
Torso	50	284
Upper Limbs	68	200
Lower Limbs	94	374
Subtotal	221	885
Complete Standing Configuration	557	2518
Unique to Seated Configuration:		
Torso	12	62
Upper Limbs	70	214
Lower Limbs	86	362
Subtotal	168	638
Complete Seated Configuration	504	2271



(a) As Drawn by the Artist

(b) As Plotted by the Graphics Option of MEVDP

FIGURE 3.-vertical selections of head.

Weight

The weights of the standing and seated model configurations are 155.5 and 150.6 lb, respectively. These weights are well within the maximum permissible error of 16.2 lb from the nominal weight of the 50th percentile Air Force man, 161.9 lb. The weights of the model elements are summarized in table 3. Note that the weight of the skeleton is in close agreement with the weights due to Morgan[3] and Long.[4] The weights of individual organs also compare favorably to weights listed by Morgan. A complete description of the Computerized Anatomical Model Man is available in the final report of the study.[5]

Application of the Computerized Anatomical Model Man to Mission Planning

The following examples show how the computerized anatomical model man could influence the conclusions of studies of missions in which radiation is a factor.

TABLE 3.-Summary of model man weight.

Body Region	Tissue	Skeleton	Organ
Common to Both Standing and Seated Configurations:			
Head	4.5	1.6	2.6
Torso	28.1	11.4	17.1
Upper Limbs	0.7	0.7	--
Subtotal	33.4	13.8	19.7
Unique to Standing Configuration:			
Genitals	0.2	--	0.0
Torso	17.6	0.9	1.5
Upper Limbs	15.8	1.5	--
Lower Limbs	44.9	5.6	--
Subtotal	78.5	8.1	1.6
Complete Standing Configuration: Total, Each Material	112.0	22.0	21.4
Grand Total	155.4		
% Error in Grand Total	3.9		
Unique to Seated Configuration:			
Genitals	--	--	0.0
Torso	9.4	0.2	1.4
Upper Limbs	14.4	1.5	--
Lower Limbs	49.5	6.6	--
Subtotal	73.5	8.4	1.5
Complete Seated Configuration: Total, Each Material	106.9	22.2	21.3
Grand Total	150.5		
% Error in Grand Total	6.9		
Note: 50th Percentile Air Force Man Weighs 161.9 lb.			

The principal effect of the model man is on the mass, or areal density distribution, of the materials surrounding the location at which the dose is to be calculated. The areal density distribution results from inert materials (such as metal, plastics, glass, and propellant) that contribute to the shielding due to the spacecraft and its equipment, and living tissue (such as muscles, bones, and organs) of the astronaut and his companions. The typical distribution obtained by systematically calculating the mass of material per unit area per unit solid angle throughout all space surrounding a chosen dose point is shown in part a of figure 4. Because the order in which this histogram is arranged has no effect on the results, it is convenient to re-arrange the values in order of increasing areal density, as shown in part b of figure 4. The latter curve provides insight into ways to improve the areal density distribution of a man in a spacecraft.

Since the contribution to the radiation dose is much greater from the lower areal density region near the origin of the curve, increasing the shielding mass in this region will reduce the radiation dose. Some degree of optimization of the areal density distribution can be achieved by redistributing the mass of the spacecraft and by suitably locating and orienting the crew. However, the natural mass distribution, or self-shielding of the human body, is not ideal, especially when the astronaut is slim and tall.

At some dose locations, the areal density distribution is enhanced by the precise configuration of the complete model man, where more dense muscle and skeletal tissue may surround the dose point. In other cases, the proximity of lower density lung or intestinal tissue may have unfavorable effects. Accordingly, the use of this model will, in some instances, result in lower radiation doses, and in other instances, higher doses than would be predicted from a less precise model of man.

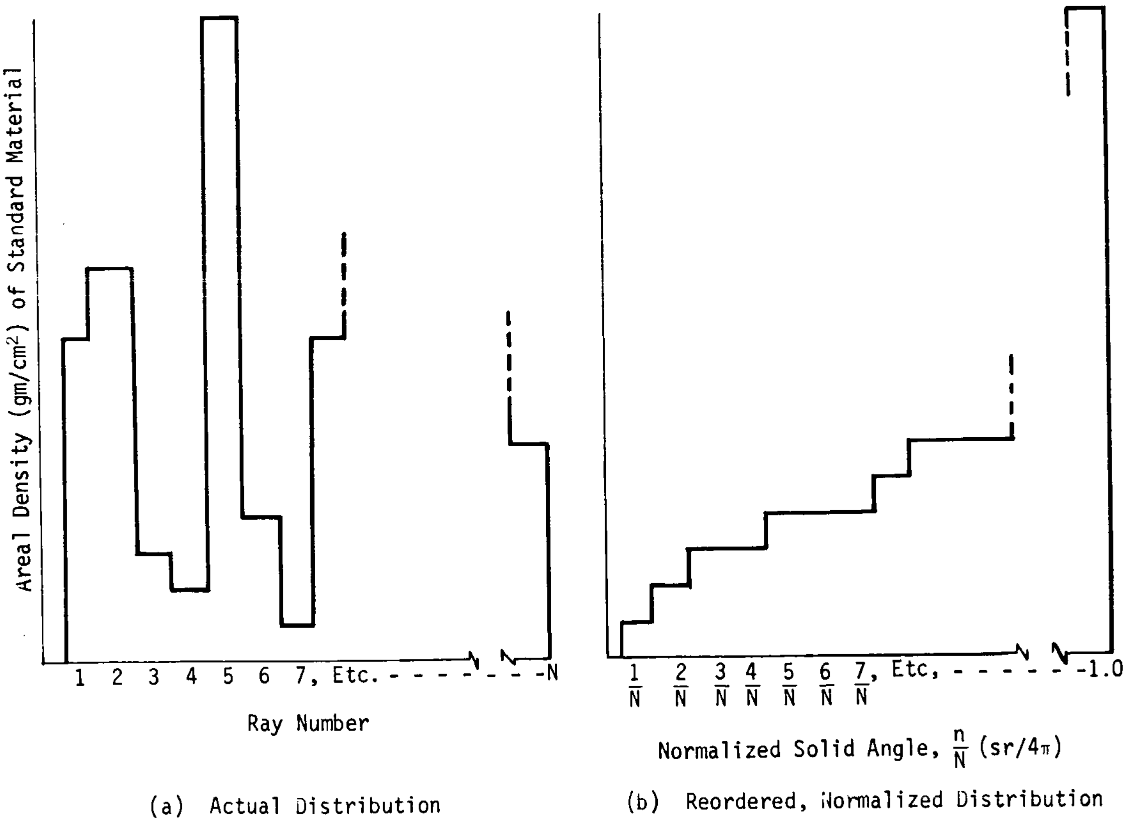


FIGURE 4.-Interpretation of areal/density distribution.

The other effects of the computerized model man on radiation analyses are largely predetermined by the combined areal density distribution of the man and his spacecraft. In sequence of calculation, the first effect is on the differential kinetic energy spectrum, shown schematically in figure 5. The incident spectrum is the uppermost curve. The effects of increasing protection against the spectrum of the radiation arriving at the dose point are also indicated.

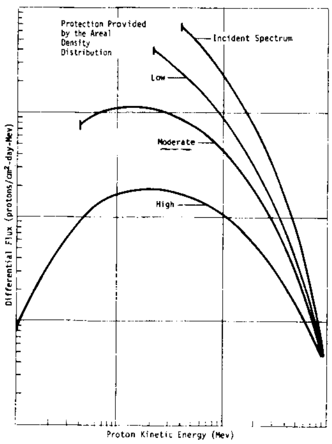


FIGURE 5.-Schematic representation of effects of area/density on differential spectrum arriving at a detector.

The total number of radiation particles that reach the dose point is obtained by integrating the differential kinetic energy spectrum. From this number, the fraction of the incident particles allowed to reach the dose point by the areal density distribution is readily calculated.

The final effect of the model is on the radiation dose absorbed by standard tissue. This has been calculated by conventional techniques from the total radiation spectrum at the dose point and from the stopping power of protons in the tissue of a radiation standard man with the composition suggested by Morgan.[3]

The first two examples of applications of the computerized anatomical model man are for a spacecraft and mission orbit similar to those planned for Skylab. The orbit is circular at an altitude of 235 nautical miles and is inclined 50 degrees. The incident radiation environment is composed of protons with energies from 4 to 5000 Mev, as defined by the Vette models of the Van Allen belt. The model of the spacecraft is a simplified version of the orbital workshop without the interior accommodations, solar panels, or attached modules that will actually be provided in the Skylab orbital assembly.

First, comparisons have been made of the radiation arriving at selected dose points in the computerized model man. The combined areal density distributions of the model man and spacecraft surrounding each dose point and the distribution due to only the spacecraft are shown in figure 6. Note that the self-shielding of the model man is of considerable benefit throughout the space surrounding the dose point. The spectra of protons arriving at the dose points are compared with the incident spectrum in figure 7, and are consistent with the areal density distributions. The remaining effects are summarized in table 4. Note from this table that the differences between the doses are small for points near the surface of the body, such as at the lens of the eye and the skin of the chest. This is to be anticipated because the greatest portion of the radiation arrives from the relatively large region of space where there is little or no intervening tissue. When the dose point is well within the interior of the body, such as in the intestine or femur, the variations of tissue composition and density have larger effects.

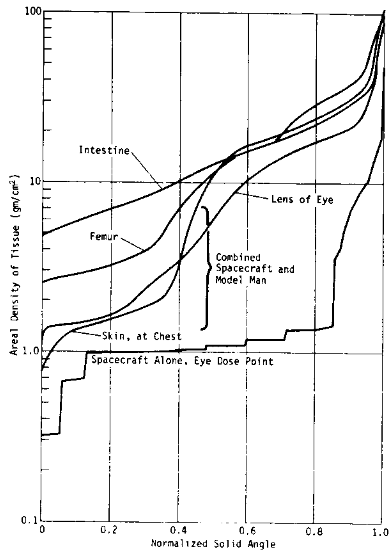


FIGURE 6.-Comparison of area/density distribution at selected dose points.

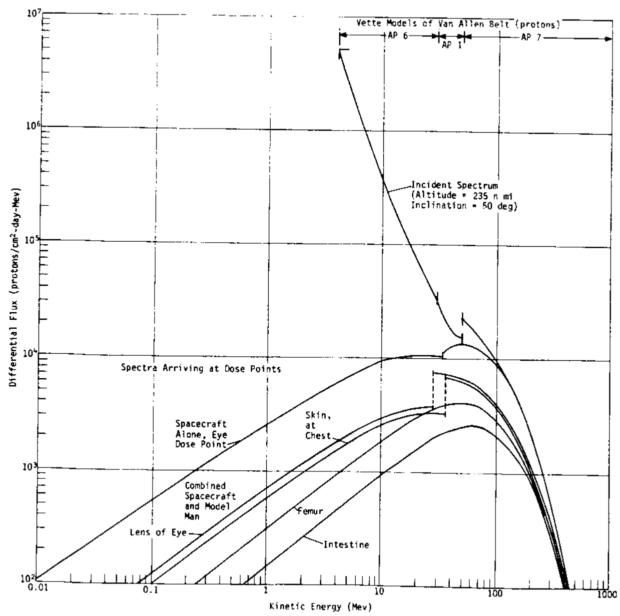


FIGURE 7.-Comparison of differential kinetic energy spectra of protons arriving at selected dose points.

TABLE 4.-Results of radiation analyses for several dose locations.

Dose Point	Minimum Areal Density (gm/cm^2)	Fraction of Incident Protons Transmitted		Radiation Dose (rad/month)
		From Exterior	From Interior	
Lens of Eye	1.218	0.067	0.54	4.55
Skin, at Chest	0.813	0.061	0.49	4.14
Intestine	4.881	0.034	0.28	1.97
Femur, Blood-Forming Center	2.552	0.047	0.38	3.09
Spacecraft Only, Point at Location of Lens of Eye if Man Were Present	0.322	0.123	1.000	10.42

A second application of the model man is to the evaluation of local shielding, or protection, such as goggles for the eyes. In this example, the goggles have lenses 2 inches in diameter and are of various thicknesses. The effects of the goggles on the areal density distribution and the differential kinetic energy spectrum at the lenses of the eyes are shown in figures 8 and 9, respectively. The fractions of the incident particles transmitted by the spacecraft and by the combined spacecraft and model man, and the resulting monthly radiation doses are plotted in figures 10 and 11, respectively.

Because the goggles provide shielding from a large region of space that would normally be open to radiation, thin glasses provide substantial protection. In fact, if the goggles were fit closer to the head than in this example, the areal density distributions near the origin of figure 8 would be considerably improved. Even so, figure 11 shows that the man's self-shielding reduces the radiation dose to less than 50% of that which would be measured by a point detector at the eye location if the man were absent.

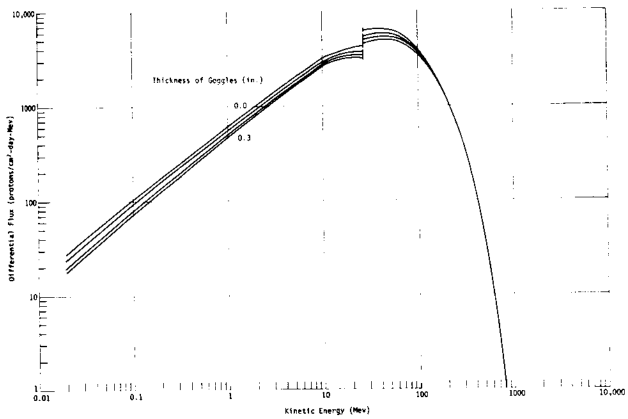


Fig. 9 Effect of Goggles on Differential Kinetic Energy of Spectra Arriving at the Lens of the Eye

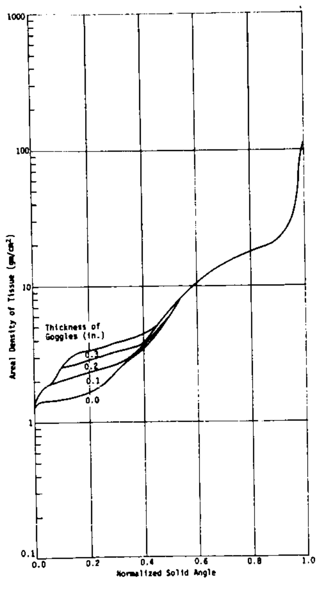


Fig. 8 Effect of Goggles on Areal Density Distribution Protecting the Lens of the Eye

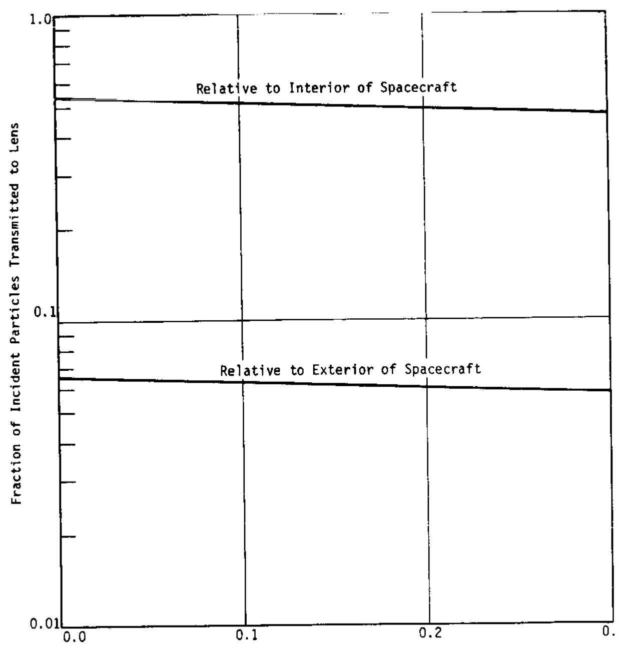


Fig. 10 Effect of Goggles on Number of Protons Transmitted to the Lens of the Eye

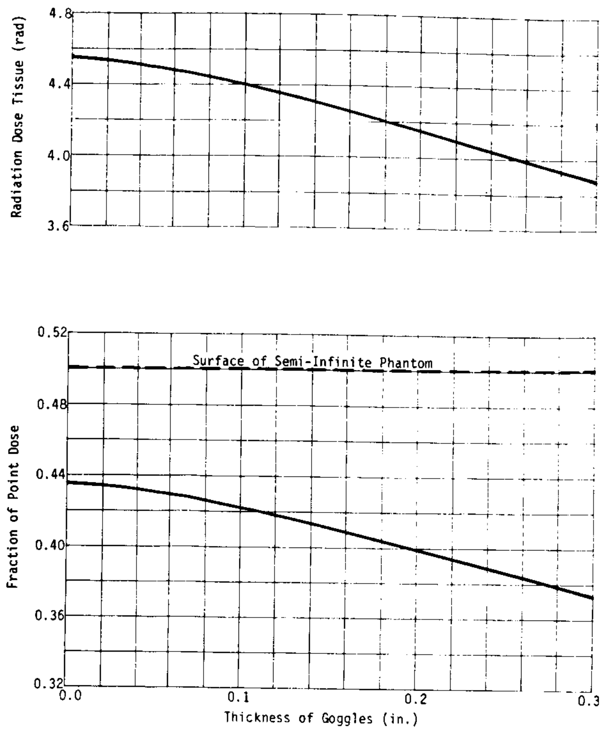


FIGURE 11.-Effectiveness of goggles in reducing the radiation dose absorbed by the lens of the eye.

The final application of the computerized anatomical model man was suggested in an interview with Dr. R. E. Benson of NASA referring to light flashes observed by the astronauts during Apollo flights 11, 12, and 13.[7] It was stated that cosmic radiation was a possible source of these flashes. To test this possibility, a calculation was made for the seated configuration of the model occupying the Apollo Block II Command and Service Module. A model of the cosmic ray environment due to Barrett[6] was assumed. To represent the conditions in cislunar space, perturbations of the environment due to the geomagnetic field were ignored. The combined areal density distribution of the seated model man and the Apollo are shown in figure 12 to range from 4.6 to 840 gm/cm^2 when the dose location is the retina of the right eye. This figure also shows that the areal density in 85% of the space surrounding the dose point is less than 50 gm/cm^2. When this areal density is combined with the Barrett spectrum, in which all particles have energies greater than 800 Mev, the spectrum at the retina appears as shown in figure 13. Though the high-areal-density region of figure 12 slows some of the particles, as shown at the lower left portion of figure 13, 96.8% of the incident particles still arrive at the retina of the eye.

According to Dr. Benson,[7] the frequencies of the light flashes observed by the Apollo 13 astronauts were as follows:

James Lovell	One every 2 minutes
Fred Haise	Ten in 5 minutes
John Swigert	Two in 30 minutes

The primary component of the cosmic radiation is the proton. In Barrett's model, the proton rate is 2.2 per second. This rate is considerably higher than reported in the article. The abundances of heavier particles are far less than protons -- only 12.5% for alpha particles and 1.6% for the total of all heavier particles. The rate of heavier particles is about two per minute, and is consistent with the observations of Lovell and Haise. It is therefore possible that these particles were the source of the light flashes.

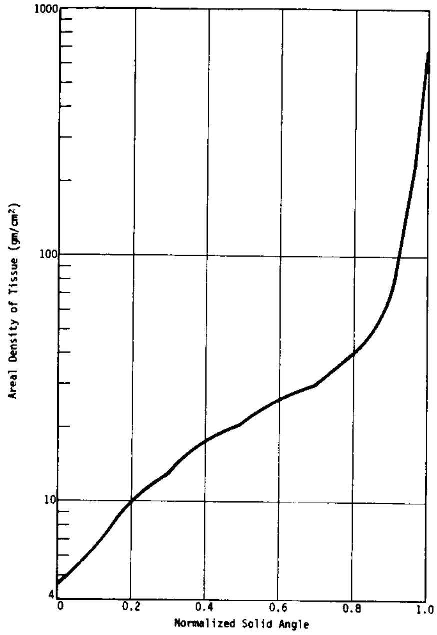


Fig. 12 Areal Density Distribution about the Retina of the Eye, Seated Configuration of the Model Man in the Apollo Command and Service Module

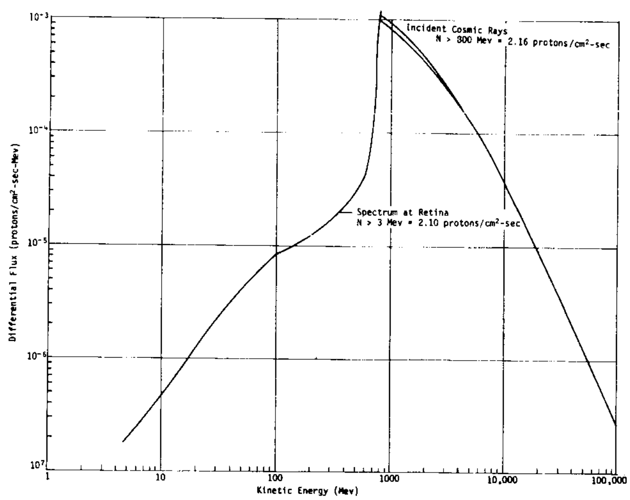


Fig. 13 Effective Cosmic Ray Spectrum at the Retina of the Eye, Seated Model Man Combined with Apollo Command and Service Module

Concluding Statement

The U. S. Air Force and NASA have jointly sponsored the development of a detailed model of the geometrical conformation, density distribution, and chemical composition of a typical astronaut. Its application is to the precise calculation of the combined areal density distribution surrounding a dose location due to the shielding provided by the astronauts and their spacecraft. From this information, radiation spectra and doses may be calculated. The results of radiation analyses employing this model could influence mission planning and operations.

Several examples of applications for the computerized anatomical model man have been discussed in this paper. Studies indicate that this model is best suited for analyses of radiation doses well within the body, where the effects of variations of tissue density and chemical composition are likely to be most significant. When the dose point is on or near the surface of the body, other effects, such as the astronauts' location and orientation with respect to the spacecraft, are probably more important.

In addition to its usefulness for depth/dose calculations, the model is appropriate for the evaluation and optimization of local protection, such as goggles or body shielding, especially when the effect of the local shielding is of the same order of magnitude as the effect of the self-shielding of the body. When the radiation is very penetrating, as in the case of cosmic radiation, the details of the spacecraft and human configurations are relatively unimportant: that is, the configurations are most influential when the most populous, lowest-energy portion of the incident spectrum is stopped.

References

1. Hertzberg, H. T. E.; Daniels, G. J.; and Churchill, E.: *Anthropometry of Flying Personnel, 1950.* WADC-TR-52-321 (AD47953), Wright Air Development Center, Dayton, Ohio, September 1954.

2. Liley, B.; and Hamilton, S. C.: *Modified Elemental Volume Dose Program (EVDP).* AFWL-TR-69-68, North American Rockwell Corporation, Los Angeles, California, August 1969.

3. Morgan, K. Z., Editor: "Report of ICRP Committee II on Permissable Dose for Internal Radiation (1959)," *Health Physics,* vol. 3. Pergamon Press, Inc., New York, New York June 1960.

4. Long, C., Editor: *Biochemists' Handbook.* D. VanNostrand Company, Inc., Princeton, New Jersey, 1968.

5. Kase, P. G.: *Computerized Anatomical Model Man.* AFWL-TR-69-161, Martin Marietta Corporation, Denver, Colorado, October 1969.

6. Barrett, P. H.; Bollinger, L. M.; Cocconi, G.; Eisenberg, Y.; and Greisen, K.: "Interpretations of Cosmic Ray Measurements for Underground," *Reviews of Modern Physics,* vol. 24, 1952.

7. "Apollo 14 Will Probe Light Flashes," *Aviation Week* and *Space Technology,* June 15, 1970.