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PRELIMINARY ANALYSIS OF THE IMPLICATIONS OF NATURAL RADIATIONS ON GEOSTATIONARY OPERATIONS

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16 Abstract

The natural radiations present at geostationary orbit are the galactic cosmic rays, geomagnetically trapped radiation, and solar cosmic rays. The low-level galactic cosmic rays are important for careers spending a year or more at geostationary altitude. The trapped radiation undergoes large fluctuations and will on occasion require interruption of extravehicular activity (EVA). The space-suit shield requirements are strongly affected by the number of interruptions allowed. EVA cannot proceed during a large solar event and maximum allowable doses are exceeded in a few hours unless a heavily shielded area is provided. A shelter of 10 g/cm^2 with personal shielding for the eyes and testes would contain exposure to within the presently accepted exposure constraints. Since radiation levels can increase unexpectedly to serious levels, an onboard radiation monitoring system with rate and integration capabilities is required for both surface-dose and depth-dose monitoring. Since the radiation protection requirements for any segment of a mission are affected by the overall mission dose profile, an accurate shield and operations analysis must await the development of a radiation model suited for the needs of manned space operations.

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SUMMARY

The natural radiations present at geostationary orbit are the galactic cosmic rays, geomagnetically trapped radiation, and solar cosmic rays. The galactic cosmic rays provide a low-level background and are important for astronauts whose careers include a year or more at geostationary altitude. The trapped radiations undergo large temporal fluctuations (up to three orders of magnitude). There is a persistent diurnal variation so that extravehicular activity (EVA) should be centered about the radiation minimum near local midnight. During geomagnetic fluctuations, the trapped radiation will, on occasion, require EVA interruption. The spacesuit shielding requirements are strongly affected by the number of interruptions allowed within the mission. A spacecraft wall of 2 g/cm^2 is inadequate for protection from the extremes of trapped radiation so that a thicker wall or a radiation shelter area is required. EVA cannot proceed during a large solar event in which maximum allowable doses are reached within a few hours unless a heavily sheltered area is provided. A shelter of 5 g/cm^2 thickness is sufficient to control the early somatic response and would cause no significant risk to mission safety. However, the risk of late effects is considered to be unacceptable. A shelter of 10 g/cm^2 with personal shielding for the eyes and testes during

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peak exposure would maintain doses from a major solar event to within the presently accepted exposure constraints. Since radiation levels can increase unexpectedly to serious levels, an onboard radiation monitoring system with rate and integration capabilities is required for both surface-dose and depth-dose monitoring. An audioalarm system directly connected to voice communications is recommended to signal the astronauts when dangerous radiation levels are obtained. Since the radiation protection requirements for any segment of a mission are affected by the overall mission dose profile, an accurate shield and operations analysis must await the development of a radiation model suitable for manned space operations. In particular, an environmental model giving short-term average median fluence and short-term average fluence variations for time periods ranging from a few days to several months is required.

INTRODUCTION

Because of the exceptional importance of geostationary orbits to communications and Earth observations and anticipated use for possible power transmission or solar power generation (ref. 1), it is expected that geostationary operations involving the space transportation system will be among the most important objectives of the future space program. Construction of large space facilities requiring long stay periods with extensive extravehicular activity (EVA) is envisioned as being of particular importance with regard to power applications. In this connection, special attention must be given to the radiation protection requirements of such operations. The purpose of this report is to present results of the analysis of such requirements on the basis of currently available environmental information.

A review of the environmental data available in 1962 was made by Foelsche (ref. 2) and corresponding estimates of doses are contained therein. The only major solar particle event which has been observed since that time is the event series commencing on

August 2, 1972, and continuing through August 11, 1972 (refs. 3 to 5). This August 1972 event series is the most significant event in terms of manned space operations outside or near the edge of the Earth's magnetic field (as is the case for geostationary operations). The knowledge of the outer zone electrons has greatly improved since 1962 and resulted in the publication of a detailed environmental map AE2 in 1966 (ref. 6). Although representative time variations are given in reference 6, the purpose of the AE2 model was to determine long-term average fluence appropriate for use in unmanned spacecraft design for long-term missions of a year or more. To meet the special needs of geosynchronous operations, a new model was developed in which variations were analyzed in detail. The mean local time variation was extracted and short-term fluctuations were given by a statistical representation.

This new model (AE3) for synchronous altitudes was published in 1967 (ref. 7). In the period following the development of the AE3 model, detailed data were being obtained by geostationary satellites (most notably the ATS 1) in which detailed time variations were studied. Although the AE3 mean local time variations were largely confirmed by these measurements, there were significant discrepancies in the statistics of short-term fluctuations (ref. 8), especially for the most penetrating electrons (particle energy $E > 1.9$ MeV). The accumulation of data measured in the years following 1966 led to the issuance of a new outer zone electron model AE4 in 1972 (ref. 9); detailed comparison with measured data is given in reference 10. Detailed comparisons of the new electron models AE4 (ref. 9) and AE5 (ref. 11) with the previous models AE2 and AE3 are given in reference 12. The mean electron flux and its local time variations now seem to be well established and the statistics of fluctuations appear to be accurately known.

If long time periods are required to accumulate a significant dose, then short-term fluctuations will not be important insofar as the accumulation of serious radiation levels is concerned. Previous calculations of doses due to outer zone electrons have been made on the basis of the median dose (time-averaged log fluence) which is given by standard environmental models such as AE2 or the 50-percentile environment of AE3 (refs. 13 to 15). Although statistical fluctuations were noted by Curtis et al. (ref. 15) as being important for EVA, such effects were not explicitly treated.

The purpose of the present report is to evaluate the impact of natural radiations on geostationary operations and to consider radiation protection requirements to insure safety. In the following, a brief discussion of the radiation environment at geostationary altitudes is given. Methods of estimating doses are discussed and are followed by a presentation of dose rate, dose histories, and dose fluctuations. On the basis of these data, the impact on mission operations is discussed along with shielding and dosimetry requirements for the space vehicle and during EVA.

The authors acknowledge the useful discussions with J. V. Bailey and A. C. Hardy of Johnson Space Center, M. O. Burrell and J. W. Watts of Marshall Space Flight Center, and E. G. Stassinopoulos of Goddard Space Flight Center during the course of this work.

SYMBOLS

$D(x,t)$	dose at point x at local time t, rad (or rem) (1 rad = 10^{-2} J/kg)
E	particle energy, MeV
E_e	electron energy, MeV
H_α	first line in Balmer series (6562 Å)
K_p	planetary magnetic index
r	radius of tissue sphere, g/cm^2
r_e	radius of Earth, 6378 km

t local time, hr

UT universal time

$\vec{x}$ vector to dose point, cm

An arrow over a symbol denotes a vector.

GEOSTATIONARY ORBIT RADIATION ENVIRONMENT

The radiations present at geostationary orbits ($r = 6.63r_e$ with 0^o inclination) consist of the galactic cosmic rays, geomagnetically trapped radiation, and transient solar cosmic rays. The galactic radiation reaches the geostationary orbits unhindered by the geomagnetic field to produce a low level of background radiation and is regarded to be of little or no significance for exposures lasting for a few months, or less. Although galactic radiations are important for extended operations, the belt radiation and solar cosmic rays are of major concern to geostationary operations of short as well as extended duration and are considered in detail.

Belt Radiation

The outer belt radiation consists mostly of electrons and protons. The protons are of low energy (less than 2 MeV) and are stopped by even the lightest weight spacesuit whereas the electrons are very energetic (to several MeV) and appreciable numbers will penetrate more than 1 centimeter of tissue. These outer belt radiations undergo large temporal variations as related to long-term-average solar activity (ref. 12), 27-day variations associated with solar rotation (ref. 16, related to passage of sector boundaries), geomagnetic storms due to solar flare events (refs. 8, 16, and 17), geomagnetic fluctuations associated with substorms (refs. 8, 16, and 17), and variations associated with local time (ref. 7). The long-term variations result from the greater average plasma output from the Sun during solar active years. The average location of the outer belt maximum moves from its position near $5r_e$ at solar minimum inward to about $3r_e$ at solar maximum. This shift in maximum intensity is not so much associated with actual movement of the belt region but rather appears as a filling up of the slot region (ref. 17). At geostationary altitudes, the time-averaged electron flux varies only slightly (about a factor of two or less) as a function of average solar activity (refs. 10, 12, and 17). The effect of solar rotation is minor and is completely masked by short-term variations during years of increased solar activity (refs. 8 and 17). Short-term variations are associated with geomagnetic disturbances. During intense magnetic storms, intensities in the geostationary orbit are observed to increase by more than two orders of magnitude in a few hours followed by decay with a mean lifetime of several days (ref. 8), as shown in figure 1. Note the correlation between intensity and K_p indices. During such flux increases it appears that large electron populations are injected into the outer zone through the magnetic tail and are followed by radial diffusion inward to the slot region (ref. 9). Short-term variations associated with geomagnetic field fluctuations appear to vary by a factor of two or three in the course of a few hours and by an order of magnitude over a day or more. Small-scale fluctuations associated with periodic drift echoes are also observed during geomagnetically active times (ref. 8). There are further diurnal variations of as little as a factor of 2 and as large as a factor of 13 depending on electron energy and phase of the solar cycle. The minimum intensity occurs 1 hour before local midnight and maximum intensity is 1 hour before local noon (refs. 8 and 10). The environmental models of outer zone trapped radiation have greatly improved in the period following 1969 especially at geostationary altitudes covered by the ATS 1 satellite (ref. 9). The trapped electron belt has more energetic electrons than that predicted by the AE3 model (refs. 8, 9, 10, and 12) and a factor of 10 increase in doses brings the results of the shielding calculations of

Burrell et al. (ref. 14) into better agreement with the new AE4 model. The results of reference 14 increased by a factor of 10 will be used here and it is assumed that EVA is mainly affected by the presence of the belt radiations and that EVA will be conducted near local midnight to minimize exposure. It is understood that during large-scale fluctuations due to geomagnetic disturbances, EVA will cease and shelter within the vehicle interior is assumed. As will be shown later, the inherent shielding provided by a typical vehicle is insufficient to provide adequate protection against the belt radiations. Clearly, an updated assessment of the impact due to the belt radiation on operations is required.

The fluctuations in the outer belt radiations, if sampled at random times, form a statistical sample which appears to have a log normal distribution as shown in figure 2. The mean log flux corresponds to the 50-percentile flux and the mean flux is nearly the 80-percentile flux (ref. 15) since the log normal distribution is skewed to the right. The standard outer zone environmental models are presented as the mean log flux and dose rates calculated from, for example, the AE3 map in the outer zone will be exceeded 50 percent of the time. If the exposure times are long compared with the short-term fluctuations, then the dose received will be about a factor of three higher than that predicted by the mean log flux model. If the mission duration is on the order of (or less than) the short-term fluctuations, then the mission dose will be distributed with the same statistical distribution as the observed flux. There is a smooth transition between the models for very short and very long missions although the necessary data have not been compiled.

The available dose calculations were made by using the AE3 mean-log-flux model (ref. 14) for isotropic incidence on one side of a plane. It is assumed here that the high-energy electrons are most important in causing the dose behind the shields of interest; thus, the dose distribution is assumed to be determined by the mean-log flux and the high-energy log-flux variance. The log-flux variance at 2 MeV is approximately 0.7 so that the $\pm 1\sigma$ range of the dose will be found by using the factors $10^{\pm 0.7} \approx 5^{\pm 1}$. The 50-percentile dose rate (increased by a factor of 10 to better approximate AE4) in units of rad per hour as calculated by Burrell et al. (ref. 14) can be approximated by

$$D(x,t) = 8750 \exp(-10.6x - 1.47 \cos \omega t) + 0.19 \exp(-0.366x - 1.15 \cos \omega t) \quad (1)$$

where $\omega = 2\pi/24$, t is local time in units of hours, and x is shield thickness in units of g/cm^2 of aluminum. The first term corresponds to the dose due to electrons and the second term is the bremsstrahlung dose. Doses for mission durations from a few hours up to several days may be estimated by using equation (1) with the $\pm 1\sigma$ values found by applying the factors $5^{\pm 1}$. Mission doses for several days to a few months duration are beyond the scope of existing environmental models. Equation (1) and the statistical treatment used nere imply the same time structure during times of geomagnetic disturbance. The time dependence in equation (1) is not in fact observed during geomagnetic disturbances. (See ref. 8.) This model is used in subsequent analysis.

Solar Cosmic Rays

Depending on the local solar magnetic-field structure, a quantity of energetic particles may be accelerated and ejected during some solar-flare events. A solar flare is always observed optically (usually in H_α and very rarely in the white continuum) and ejection of a plasma from the flare region is noted by the presence of a Type IV radio burst produced as synchrotron radiation by relativistic electrons in the region of the solar corona (ref. 18). The Type IV radio burst indicates that an efficient acceleration of ions in the chromosphere has occurred and the intensity of the Type IV radio burst is taken as an indication of the amount of plasma ejected (ref. 18).

The high and intermediate energy particles move quickly away from the flare region and follow a spiral path about the sectored solar magnetic field lines into which they were accelerated (ref. 19). If those sectored lines intersect the Earth, then an appreciable particle increase is typically observed in 20 to 30 minutes for relativistic particles and at later times for lower energies. (See refs. 18 to 20.) If the sectored lines do not intersect the Earth, then the energetic particles propagate on past the Earth's orbit to the turbulence region where the solar wind and interstellar space merge; some are reflected backward into the solar cavity and particle increases at the Earth are observed only after a number of hours (ref. 18). If the particle event was preceded by earlier events, then the interplanetary fields may be distorted and, as a result, cause unusual time delays in particle arrival at the Earth. (See refs. 19 and 20.) The history of solar particle events varies greatly from event to event, depending on a complex combination of conditions, many of which are not even observable from the Earth. Of the events most important to manned space operations, the onset time varies from 20 minutes to several hours, and the rise time varies from 15 minutes to a few hours after onset. The peak intensity may last only intermittently or for a few hours, decay of the event occurring within a few hours to a few days. (See refs. 2 and 18 to 21.) As solar events vary greatly with respect to time history, they also vary in peak intensity and energy spectrum.

The events of solar cycles 19 and 20 were considered in establishing the range of fluences which have been observed near the Earth in the past two decades. The integral particle fluence from three of the larger events is shown in figure 3. The February 23, 1956, and November 1960 data were taken from reference 20 below 100 MeV, and references 2 and 21 above 100 MeV. The August 1972 data were obtained by integrating the results measured by the experiments of C. O. Bostrom of the Applied Physics Laboratory of Johns Hopkins University on the IMP 5 and 6 satellites. The IMP data were extrapolated above 60 MeV according to the spectrum of the form $\exp(-E/28)$ where E is the proton energy in units of MeV. This spectral extrapolation is in rough agreement with the spectrum found by King (ref. 4) to be in agreement with the experimental measurement of Bazilevskaya et al. (ref. 22). The high-energy fluence from these events is also observable in the ground level event data (refs. 23 and 24). It is clear that maximum fluence between 10 and 100 MeV was generated by the August 4, 1972, event. Above 100 MeV, the most intense event appears to have been the February 23, 1956, event. All the major event series seem to lie nearly between the limiting curves composed of the August 1972 and February 1956 events shown in figure 3 as, for example, the curve shown for the November 1960 event series. The maximum doses from any observed event should be less than the largest dose caused by either of these two events. When considering space operations in geostationary orbits, near 6.63 Earth radii, it is observed that protons of energies greater than 10 MeV have direct access to this portion of the geomagnetic field (refs. 8 and 25). Although quasi-trapping at the lower energies occurs, the lifetimes are sufficiently short that there is no significant temporary storage (ref. 25). The dose and dose equivalent calculated by using the International Commission for Radiological Protection (ICRP) defined quality factor (ref. 26) in the center of a tissue sphere for the February 1956 and August 1972 events are shown in figures 4 and 5, respectively. Clearly for space operations, where shielding dimensions (including self-shielding) are mostly less than 10 g/cm^2, the August 1972 event would have had the greatest impact.

The accumulated fluence for August 4 through August 5 is shown in figure 6 (accumulation starts on August 2, 1975). The lowest curve is the accumulated fluence approximately 40 minutes after the optical flare was observed on August 4. The low-energy fluence above the break in the curve is mostly protons produced by an earlier event on August 2. The high-energy shoulder in this curve marks the onset of energetic particles produced by the August 4 flare. The accumulated fluence during the succeeding 15 hours of August 4 is shown as is the fluence through August 5 at 1000 UT at which time the event had nearly ceased. These curves were generated by using the IMP data of C. O. Bostrom to 60 MeV and high-energy extrapolation according to $\exp(-E/28)$. The dose accumulated in the center of a sphere of radius r is shown for August 4 and 5 in figure 7 with corresponding dose equivalent in figure 8. The calculations of doses within a space vehicle and in a spacesuit are now considered.

ASSUMPTIONS IN DOSE ESTIMATES

Whenever the proton fluence is spatially uniform, the dose at a point $\vec{x}$ in a convex object may be calculated (ref. 27) by

$$D(\vec{x}) = \int_0^\infty \int_\Omega R_n[z_x(\vec{\Omega}),E]\ \phi(\vec{\Omega},E)\ d\vec{\Omega}\ dE \qquad (2)$$

where $R_n(z,E)$ is the dose at depth z for a unit fluence of normal incident protons of energy E on a tissue slab (ref. 28), $\phi(\vec{\Omega},E)$ is the differential proton fluence along $\vec{\Omega}$, and $z_x(\vec{\Omega})$ is the distance from the boundary to the dose point $\vec{x}$ along the direction $\vec{\Omega}$. If the radiation is isotropic, then the calculation may be further reduced (refs. 29 to 31) to

$$D(\vec{x}) = 4\pi \int_0^\infty \int_0^\infty R_n(z,E)\ f_x(z)\ \phi(E)\ dz\ dE \qquad (3)$$

where $f_x(z)$ is the areal density distribution about the dose point.

Introducing the quantity

$$D_s(r) = 4\pi \int_0^\infty R_n(r,E)\ \phi(E)\ dE \qquad (4)$$

results in

$$D(\vec{x}) = \int_0^\infty D_s(z)\ f_x(z)\ dz \qquad (5)$$

where $D_s(r)$ is the dose in a sphere of radius r. Assuming isotropy allows one to calculate the dose in any arbitrary convex object from results in figures 4, 5, 7, and 8.

It is clear from the developments in reference 27 that equation (2) with $R_n(z,E)$, the appropriate electron kernel, and $\phi(\vec{\Omega},E)$, the corresponding electron flux, may be used to estimate the dose since the dose distribution from a point monodirectional source of electrons is reasonably confined to the ray along the initial direction. Although this dose distribution is followed by electron doses, the divergence from the ray is greater than that for protons. As a result, the electron doses estimated from equation (2) may lead to a considerable overestimate whereas proton doses estimated from equation (2) are very accurate. (See ref. 27.) It is also worthwhile to note that equation (2) as applied to electrons is the standard procedure for evaluating electron and bremsstrahlung doses in complex geometry. (See ref. 32.)

Self-Shielding

In order to simplify the analysis of doses to body organs, an equivalent sphere model (refs. 30 and 33) in which the bone marrow dose is taken as one-half the dose in a 5 g/cm^2 tissue sphere is used. It is further assumed that the marrow dose is equal to the dose in the gastrointestinal tract (GIT) and the gonads. The skin dose is taken as one-half the dose in a 1-mm tissue sphere and skin dose is approximately equal to the dose in the lens of the eve. Taking the GIT dose as equal to the marrow dose results in an overestimate on the order of 30 percent or less. Taking the gonad dose as the marrow dose results in an underestimate of less than 25 percent. Bone marrow doses are generally better than 20 percent accurate. The skin dose and lens-of-eye dose errors vary between ±40 percent or less during EVA, are approximately correct within the vehicle, and are in error by -20 percent or less within a heavy shelter. Skin doses tend to be more accurate than doses to the lens of the eye.

Space Vehicle Shielding

The mass distribution of a space vehicle is not well defined until the engineering model is established. Generally, the outer wall thickness is chosen for the purpose of micrometeoroid protection and structural integrity (ref. 34). The addition of required components to the structural shell provides increased radiation protection. The minimum wall thickness is generally about 1 g/cm^2. In the following discussion, the Skylab is used as the basis for a typical space vehicle and, in particular, the mass distribution as seen from the orbital workshop area is used. The vehicle cabin dose is then approximated by

$$D_v \approx 0.1D(z=0.04) + 0.8D(z=1) + 0.1D(z=5) \qquad (6)$$

where z is the shield thickness (in addition to the self-shielding described) about the dose point (ref. 35). It was found by numerical experimentation that

$$D_v \approx D(z=1) \qquad (7)$$

approximates equation (6) with errors less than 7 percent.

Modifying Factors

The dose equivalent using the ICRP defined quality factor (ref. 26) has been determined by use of the techniques described in references 27 and 28 wherein nuclear reaction effects are found to be very important. With regard to time-modifying factors, 80 percent of the dose was received in several hours for the August 1972 event and in only 2 hours for the February 1956 event; thus, under most circumstances, the exposures to solar radiation may be considered to be acute. The marrow distribution effectiveness factor is assumed to be unity although it may be as low as 0.8 (refs. 36 and 37) which results in a small reduction of the marrow dose.

The use of the ICRP defined quality factor is most appropriate for estimates of late somatic injury and thus for estimating contributions to career exposure limits (refs. 38 and 39). The dose equivalent, as calculated herein, is conservative with regard to early somatic effects whereas the absorbed dose is generally an underestimate (ref. 38).

DOSE FLUCTUATIONS AND HISTORIES

Manned operations in geostationary orbit will involve staying periods of several weeks or more so that some averaging over short-term fluctuations will occur. The design of living quarters may be made on the basis of long-term-averaged trapped radiation intensities provided a heavier shelter is available to protect the crew from the most extreme variations and solar cosmic rays. The main questions concerning fluctuations and time variations of the environment are with the impact of EVA and the design of a shelter area. For a given spacesuit thickness the percentage of days for which EVA can be accomplished, the regularity of possible work shifts, and the access time to a sheltered area are of fundamental concern. Although a very thick spacesuit could be used, the limits of mobility and dexterity involved may need to be traded off with disruptions and irregularity in work periods. In this section, results are derived from which such questions may be analyzed. A complete analysis of the impact of the belt radiation cannot be made at this time since existing environmental models do not contain the necessary information.

Local Time Variations

There is a persistent local time variation although it is often masked by short-term fluctuations due to geomagnetic disturbances. At other times the local time variation is greatly accentuated during disturbed periods. Although fluctuations occur on the time scale of minutes and hours, the important large-scale increases usually last from a few to several days (see fig. 1) and these fluctuations will probably result in work stoppages through such periods. Generally, work shifts will be during periods when local time variations result in minimum radiation levels. Such work periods are centered about 1 hour before local midnight.

The median electron doses as obtained by Burrell and adjusted by a factor of 10 to approximate AE4 for different shield thickness are shown as a function of the shift duration (exposure time) in figure 9. On half of the days worked, the dose would be less than that shown in the figure. To estimate shielding and shift periods with less work-loss time, the fact that the dose is a log normal distribution with a standard deviation of approximately 0.7 may be used. The fluctuations in dose for a given shield thickness as a function of shift duration are given in figures 10 to 16. The $+2\sigma$ curve corresponds to a 2.5-percent work loss and the $+3\sigma$ curve corresponds to the very rare occurrence of work loss.

The main point with regard to belt fluctuations is that a direct trade-off between spacesuit thickness and the work loss and the work period exists. Whenever work disruptions occur due to fluctuations, the work stoppage will typically last from a few to several days. Otherwise, work can proceed on a more or less regular basis.

A Solar-Event Dose History

The accumulated absorbed doses as a function of time during August 3-5, 1972, are shown in figures 17 to 21. The figures show the accumulation of skin dose and bone marrow dose for a light spacesuit, a heavy spacesuit, a typical space vehicle, a lightweight radiation shelter, and a heavyweight radiation shelter, respectively. The lens-of-eye dose is assumed to be equal to the skin dose, and the gastrointestinal tract (GIT) dose and gonad dose are assumed to be equal to the marrow dose. The dose equivalents using the ICRP quality factor may be obtained by multiplying the resultant absorbed dose by the average quality factor of 1.3. The radiation protection requirements for solar radiation are discussed on the basis of figures 17 to 21.

SHIELDING AND OPERATIONAL PROCEDURES

Exposure Limits and Rate Constraints

The career exposure limits and rate constraints which are presently used for mission planning and analysis (ref. 39) are shown in table 1. Nominal shield requirements and operational constraints are to be determined so that the limits of table 1 are not exceeded. Because of the rapid fluctuations in the belt radiations and the possibility of a large solar event, there is a chance of accidental overexposure if correct procedures are not followed. The consequences of such an overexposure are considered in a subsequent section. The shield and dosimetry requirements for a nominal operating plan and the emergency procedures are considered here.

Shielding and Operations

The shield requirements for each segment of a space mission must be determined from the combined anticipated exposure for the total mission. For example, the allowable exposure within a vehicle depends on the exposures during EVA or as anticipated from a large solar event. A large vehicle exposure limits the allowable doses during EVA so the vehicle should be made as radiation free as possible. Furthermore, if EVA is to be maximized, then the dose limits in table 1 must be approached and little or no flexibility is left in case of a solar flare event. In the present section, a simplified analysis of shield requirements is made to define the magnitude of the shield thicknesses required. The important factors for a more complete analysis are identified in this way.

Vehicle shielding.- The vehicle must shield the astronaut not only from the primary belt electrons but from the secondary bremsstrahlung as well. The electrons are mostly stopped by 2 g/cm^2 of aluminum whereas the bremsstrahlung penetrates to greater depths. Vehicle shielding is primarily a bremsstrahlung problem. Since any material tends to transmit its own bremsstrahlung, the addition of more aluminum is not a practical means of increasing shield effectiveness. A thin coating of a material with high atomic number is the only effective means of shielding the vehicle interior. The use of a material with a lower atomic number (lower than aluminum) in the outer wall would also reduce exposures. Such an outer wall with low-atomic-number material would provide a small amount of additional protection against solar protons as well (ref. 40). The precise determination of the interior wall design is beyond the scope of the present work.

Spacesuit shielding and procedures.- It is clear from figure 9 that spacesuit shielding for the belt electrons will be on the order of 0.8 g/cm^2 or more. Even at 0.8 g/cm^2, the 8-hour shift dose during minimum exposure is more than 3 rad per day on 50 percent of the days. To operate virtually uninterrupted by belt fluctuations, 8-hour shifts would require a shielding thickness in excess of 1 g/cm^2. It may be more efficient to have more than one shift per day and to allow for more interruptions. For example, it is seen in figure 14 that two 8-hour shifts per day with 50 percent work stoppage average 2.5 rad per day to each worker with a 1 g/cm^2 thick suit, as compared with one 8-hour shift per day with 2.5 percent work stoppage which results in 20 rad per day for each worker on extreme days. Detailed studies are needed to analyze the impact of work stoppages on performance since the allowance of a high percent work stoppage appears to be an attractive means to maintain low exposures without excessively thick spacesuits. It may also be that several spacesuits of graduated thicknesses would also be helpful to maximize performance on days of low radiation levels. For example, spacesuits of thicknesses in excess of 1 g/cm^2 can hold exposure to acceptable levels for at least one 8-hour shift on most of the days as seen in figures 15 and 16.

In the event of a large solar flare such as that which occurred on August 4, 1972, a spacesuit would not provide adequate protection to an astronaut, as can be seen in figures 17 to 19. An important aspect of these curves is the time required to reach exposure limits. The accepted 30-day exposure limits (ref. 39) are shown in table 2 along with the corresponding absorbed dose limits using the average quality factor of 1.3 as indicated for the August 4, 1972, event. The time required to reach the dose limits for the five shield thicknesses in figures 17 to 21 is given in table 3. Note that the exposure time starts at particle onset and not at the time of the optical flare.

It is seen from table 3 that the dose to the lens of the eye is the limiting factor at all shield thicknesses. If the helmet of the spacesuit is at least 1 g/cm^2 thick, then the skin dose is the limiting factor. Aside from the use of a thick helmet, there is little advantage of using a heavy spacesuit in the event the astronaut is involved in EVA at particle onset at least for an event like that of August 1972. The thicker suit could be of advantage for lower energy events. Otherwise, the spacesuit design will be determined on the basis of the belt radiation environment.

Radiation shelter.- The required radiation-shelter wall thickness within the vehicle is affected by the length of time required to reach the shelter area. The limiting factors within the shelter are the lens of the eye and gonad doses. The shelter requirements could be reduced by the use of personal shielding during the maximum intensity and this technique is highly recommended. In any event, the shelter wall must be near 10 g/cm^2, or more, depending on the shelter access time.

PROBABLE CONSEQUENCES OF ACCIDENTAL EXPOSURE

Since accidental exposure to a solar flare is possible if appropriate action is not followed by the astronaut, it is useful to understand the severity of the consequences in making judgments concerning a safety program. This section considers in detail some of the expected early and late somatic effects caused by the exposures noted in figures 17 to 21. First, a discussion of some of the limitations of available dose response data for humans and some of the factors that alter the dose response relations which are pertinent to space exposure are given.

The dose response relations for humans are based on observations made of individuals exposed (1) as radiation workers, (2) as patients for medical (diagnostic and therapeutic) purposes, (3) as victims during the nuclear detonations of World War II, (4) as fallout victims during nuclear testing, and (5) as victims of radiation accidents (refs. 38, 39, and 41). Late responses are judged mainly on exposures during World War II (refs. 38 and 39). Early effects are determined mainly from clinical exposures and, to a lesser extent, on criticality accidents and victims of fallout and direct radiation from nuclear blasts (refs. 38, 39, and 41).

The doses required to produce early skin effects in the space environment may be less than that observed in Earth-bound exposures due to abrasive action of the spacesuit during EVA and the individual's prior exposure history (ref. 39). Although it is usually argued that the dose required to produce the prodromal response for the astronauts is probably more than that observed for therapeutically irradiated patients (ref. 38), the situation may be actually reversed because of the stress caused by the space environment (ref. 42). This may be particularly true in a vigorous space program where astronauts are a larger and less select group of individuals. The results of the astronaut selection process are particularly evident when comparing the response of Soviet astronauts to prolonged weightless conditions with that of American astronauts (ref. 43), the latter being admitted to the program only under a more stringent set of conditions. These limitations and additional stresses during space exposure should be kept in mind with regard to the evaluation of possible consequences of exposure discussed below.

The quality factor, as established by the ICRP, pertains to late effects and should, therefore, be used in estimating contributions to career exposure limits (ref. 38). Experimental evidence indicates that absorbed dose is the determinant of early response of the skin, whereas a quality factor less than that defined by the ICRP, but greater than unity, is indicated for the prediction of early response of the blood-forming organ and the gastrointestinal tract (ref. 38).

Prior Exposure and Sensitization

Within a vehicle of 1 g/cm^2 wall thickness, doses will accumulate at an average rate of 1 rad per day on the skin and 0.2 rad per day in the bone marrow due to belt radiations (ref. 14). Doses are more likely to be determined by the extent of EVA due to the much higher dose rates in a spacesuit rather than in a well shielded vehicle. Even in a rather heavy suit of 0.5 g/cm^2, the allowable dose for that entire year could be achieved in several hours, even if the belts are undisturbed by geomagnetic activity. During geomagnetically active periods, serious exposures greatly exceeding allowable limits would be obtained in a few hours or less even within the vehicle interior unless a radiation shelter is provided. Clearly, any prior exposure would depend on the extent of EVA, geomagnetic activity, and radiation protection procedures for that particular mission.

It has been observed in animal exposures that dose levels required to produce a given effect are greatly reduced if the animal had a history of prior radiation injury even though complete recovery from the prior injury was indicated (ref. 38). The skin of the astronaut may in this way be sensitized by the belt radiation and the actual prognosis due to exposure from a solar event may be more serious than would be indicated by standard dose response relations. Adding to this sensitization is the abrasive action of a spacesuit on the skin during EVA reducing further the tolerable dose level for skin exposure (refs. 38 and 41). The doses from belt radiation are probably sufficiently low (unless extensive inner belt operations are performed) to cause no appreciable sensitization for internal organs. The following analysis of effects is based on the dose response relations compiled by Warren and Grahn in reference 41.

Early Somatic Effects

The accumulated doses for the August 1972 event are summarized in tables 4 and 5 for various shield thicknesses. In the unlikely event that the astronaut remains on EVA throughout the event, the astronaut would be disabled soon after exposure with serious medical complications within weeks due to ulceration, fluid loss, and infection of the skin. At the same time severe hematological depression would greatly complicate the medical problems. Clearly, EVA cannot proceed during a large solar-flare event.

If no additional shielding is supplied for use in the space vehicle, other than its inherent shielding capability, then the doses received can be taken as that at 1 g/cm^2. It is anticipated that erythema will occur for all personnel within the first few hours along with nausea and vomiting for about half of the crew members. There will be whole-body wet dermatitis and blistering after several days and complete epilation. Significant reductions in blood levels will occur and associated anemic response. It is clear that a sheltered area in which refuge can be taken during the few hours of greatest intensity is required.

In a light shelter of 5 g/cm^2 thickness, it is anticipated that no significant injury to the skin will occur unless the combined effect of EVA and the solar-flare radiation produces a more severe condition. There may be a slight erythema for the more sensitive individuals within a few hours and/or itching of the skin. There will be a slight depression of the blood levels that will reach a minimum after several weeks. A few incidences of vomiting and nausea will occur within the first day. There will be no serious disability. There is the possibility of some skin discomfort depending on the complications due to EVA.

In a heavy shelter of 10 g/cm^2 thickness, no significant early somatic effects are anticipated. There may be a minor depression of blood levels.

Late Somatic Effects

Insofar as late effects are determined from dose equivalents, only the results in table 5 are used. The late effects from exposures during EVA are probably precluded by the degree of early somatic injury unless shelter is obtained for at least part of the event.

If no special radiation shelter is provided for the space vehicle during an intense solar particle event, then severe late somatic injuries are expected. Permanent epilation and skin discoloration are anticipated in some cases. There will probably be temporary sterility for a year or more. There is anticipated a high incidence of lens opacities and cataract formation. There will be nonspecific life shortening of several years, in part contributed by the high exposure rates. A year or more may be required for recovery from the early response of the blood-forming organ.

Within a light shelter of 5 g/cm^2, the main late effect will be an incidence of lens opacities or cataract in 10 to 20 percent of the exposed individuals (possibly more, depending on prior exposure histories). Nonspecific life shortening of a few years, or less, is anticipated. There will probably be reduced fertility. These individuals are likely to be removed from the program to prevent further exposure.

The doses within a heavy shelter are sufficiently low that most of the 30-day exposure limits shown in table 1 are not even exceeded, or are exceeded only slightly, with the exception of the lens of the eye. A small probability of lens opacity or cataract is indicated. Additional personal shielding of the eyes and gonads during peak exposure would reduce late responses to acceptable levels.

RADIATION MONITORING AND PROCEDURES

The radiations present at geostationary orbits can undergo large fluctuations over relatively short time periods. Peak intensities have been observed to be sufficiently high that exposures in excess of allowable limits can be accumulated in 30 minutes or less. Clearly, a reliable means of in-flight monitoring with real-time capability is required to provide adequate radiation protection. Furthermore, since radiation levels sufficient to elicit severe radiation injury are easily obtained, a reliable backup monitoring system is required. Solar event forecasting could be useful to indicate periods when operational changes are needed; however, it cannot be relied upon, as will be demonstrated. Even if solar forecast reliability improves, in-flight monitoring must remain the prime source of data to govern operational procedures in the foreseeable future.

Solar Forecasting

In principle, the possibility of utilizing solar observations to indicate periods of anticipated particle events or geomagnetic activity appears to be very useful in minimizing space exposure. Even if discontinuance of EVA for a day or two during a false alarm was acceptable, the occurrence of a major event during a period of predicted low solar activity raises serious questions as to the usefulness of such a system. Consider the sequence of events during the August 1972 event series.

It was predicted on August 2, 1972, that there would be no major solar activity for the period August 3, 1972, to August 9, 1972. It appears that even as this prediction was being officially released, the August 1972 flare sequence was in progress. Among the significant ground-based observations was the large Type IV radio burst during the 3B flare of August 2, 1972, at 2005 UT. On the basis of this observed flare, the prediction of large dose rates in free space was made. The observed doses according to IMP data are shown in table 6 and are orders of magnitude less than the predicted values. A smaller 2B flare occurred on August 4, 1972, at 0621 UT for which radio output records are lacking (presumably from observational selection). Whereas only minor doses in free space were predicted for this event, it was the largest event ever observed. On the basis of ground observations, extreme measures would have been taken to protect the astronauts from the August 2, 1972, event whereas doses rose only slowly over the next 34 hours to accumulate a nearly insignificant dose. The less conspicuous August 4, 1972, event may have led one to underreact due to the cry of "wolf" only 34 hours earlier. If one did not react properly to this, in some way seemingly less important event, then severe doses would have been received over the next few hours. It is clear that solar forecasting is no replacement for in-flight monitoring.

In-Flight Monitoring

There currently appears to be no alternative to in-flight radiation monitoring. From an operations point of view, some form of warning system is required to announce when radiation levels have exceeded some predetermined action level or levels. Satellite radiation monitoring could be done if the satellite is in a geostationary orbit with nearly the same local time. (The regularity of diurnal variations especially during magnetic disturbances is not established and different geographic longitudes are at different geomagnetic latitudes.) Furthermore, if a satellite system is utilized, then the time delays due to satellite readout, telemetry, processing, and transmission must be held to a minimum. It should be further emphasized that many existing satellite detectors are directionally dependent and care must be taken in estimating doses for a given particle event. Communications must be made over frequencies that are not sensitive to atmospheric disturbances.

The most attractive means of in-flight monitoring appears to be onboard active dosimetry with rate and integration capabilities. The system should indicate surface dose and depth dose and dose rate levels both inside the crew areas and outside during EVA. This system, if attached through a pulse generator, could provide a beep over the voice communications according to the larger of either the depth dose (at 5 g/cm^2) or surface dose divided by three. The pulse could be held low enough to not intefere with normal conversation, especially at low dose rates. A suggested scale for beep rates is shown in table 7. At 1 rad/hr or less the beep rate would be 0.2 beep/sec or less; thus, activity could be taken at a more or less leisurely pace. At 10 rad/hr the 2 beeps/sec would definitely signal the astronaut that high, but not yet dangerous, levels of radiation are present and that activity is to be limited. For example, time remains to secure whatever he is working on before seeking shelter. At more than 50 rad/hr the beeps begin to merge into a continuous signal denoting that an emergency exists and that shelter should be obtained with all deliberate speed.

CONCLUDING REMARKS

The effects on geostationary orbit operations of solar radiation, and to a lesser extent belt radiation, have been considered, and shielding and monitoring requirements have been briefly discussed. It was noted that the short-term variations of the belt radiation have a large impact on radiation shield requirements and constrain extravehicular activity (EVA) to several hours around local midnight, at best, and not at all during intense geomagnetic activity. It was shown that spacesuit shielding requirements could be greatly reduced by accepting a large number of work disruptions due to radiation level enhancements. A set of spacesuits of graduated thicknesses appears to be appropriate to maximize astronaut performance on days of low radiation levels. The time average doses are not entirely meaningful for manned operations in the outer belt since large-scale fluctuations have characteristic time scales on the order of the mission duration. Examination of existing environmental models has found them to be inappropriate for manned space operations, and the development of a new model is indicated. Minimum vehicle shield requirements must be determined on the basis of the extremes of the outer belt intensities. A new analysis of the outer belt doses, especially with regard to the effects of the extremes on shield and operational requirements, should be made.

It is clear from the present analysis of solar particle events that EVA in geostationary orbits cannot be conducted during the most intense events. Furthermore, it has been shown that the usual vehicle wall thickness does not provide adequate protection without special provisions of an early warning as to when safe radiation levels are exceeded. Exposure with a lightweight shelter of 5 g/cm^2 will probably, for the most extreme solar events, produce vomiting and nausea for a few crew members, lens opacity in possibly 10 to 20 percent of the cases, reduced fertility, life shortening of a few years, and will require the exposed individuals to be removed from the program to prevent further exposure. In a shelter of 10 g/cm^2 the allowable 30-day doses are only slightly exceeded. Additional personal shielding could hold exposures to within acceptable limits.

There is little advantage in using a thick spacesuit of 0.4 g/cm^2 over a thin suit of 0.2 g/cm^2 for EVA during an event like the August 1972 event. The use of a helmet of 1 g/cm^2 or more greatly increases the stay time since the dosage to the lens of the eye tends to be the limiting factor. The design of the spacesuit depends on conditions due to belt radiation and low-energy solar events. An analysis of spacesuit requirements must await the development of a radiation model more appropriate for manned operations.

Insofar as the vehicle wall design is concerned, a thickness equivalent to at least 2 g/cm^2 of aluminum is required to stop most of the primary electrons. The major shielding problem is then against the secondary bremsstrahlung produced in the outer wall. The final weight of the wall structure is anticipated to be strongly affected by the choice of construction materials. Additional work concerning the wall structure has been suggested.

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TABLE 1.- SUGGESTED EXPOSURE LIMITS AND EXPOSURE ACCUMULATION RATE CONSTRAINTS FOR UNIT REFERENCE RISK CONDITIONS

Constraint	Ancillary reference risks				
	Primary reference risk (rem at 5 cm)	Bone marrow (rem at 5 cm)	Skin (rem at 0.1 mm)	Ocular lens (rem at 3 mm)	Testes (rem at 3 cm)
1-year average daily rate		0.2	0.6	0.3	0.1
30-day maximum		25	75	37	13
Quarterly maximum[a]		35	105	52	18
Yearly maximum		75	225	112	38
Career limit	400	400	1200	600	200

[a]May be allowed for 2 consecutive quarters followed by 6 months of restriction from further exposure to maintain yearly limit.

TABLE 2.- THIRTY-DAY EXPOSURE LIMITS

	Marrow	Skin	Lens	Testes
rem	25	75	37	13
rad*	19.2	57.7	28.5	10

*DE ≈ 1.3D where DE is the dose equivalent and D is the dose.

TABLE 3.- TIME REQUIRED TO REACH EXPOSURE LIMITS STARTING FROM THE TIME OF ONSET OF THE AUGUST 4 FLARE

Shield, g/cm^2	Marrow, hr	Skin, hr	Lens, hr	Testes,* hr
0.2	6.0	3.0	1.9	4.4
.4	6.1	3.5	2.4	4.9
1	6.3	4.7	3.6	5.2
5	8.9	8.0	6.5	7.3
10	∞	∞	11.7	12.7

*Values are overestimated since the testes dose is taken to be the same as the marrow dose.

TABLE 4.- ABSORBED DOSE TO CRITICAL ORGANS DURING AUGUST 1972 EVENTS

	Absorbed dosage with shield thickness, g/cm^2 (tissue) of -				
	0.2	0.4	1	5	10
Skin, Lens	2950	2100	1170	180	46
Marrow, Gastrointestinal tract, Gonad	173	162	137	46	15

TABLE 5.- DOSE EQUIVALENT TO CRITICAL ORGANS DURING AUGUST 1972 EVENTS

	Dose equivalent with shield thickness, g/cm^2 (tissue) of -				
	0.2	0.4	1	5	10
Skin, Lens	3835	2730	1521	234	60
Marrow, Gastrointestinal tract, Gonad	225	211	178	60	20

TABLE 6.- EXPOSURES FROM THE AUGUST 2 FLARE ACCUMULATED TO AUGUST 4 AT 0621 UT

Shield, g/cm^2	Marrow, rad	Skin, rad	Lens, rad	Testes, rad
0.2	---	50.0	50.0	---
.4	---	12.5	12.5	---
1	---	1.3	1.3	---
5	---	----	----	---
10	---	----	----	---

TABLE 7.- AUDIOPULSE RATE FOR DIFFERENT DOSE LEVELS

Dose level, rad/hr	Beeps per sec
0.1	0.02
1	.2
10	2
100	20

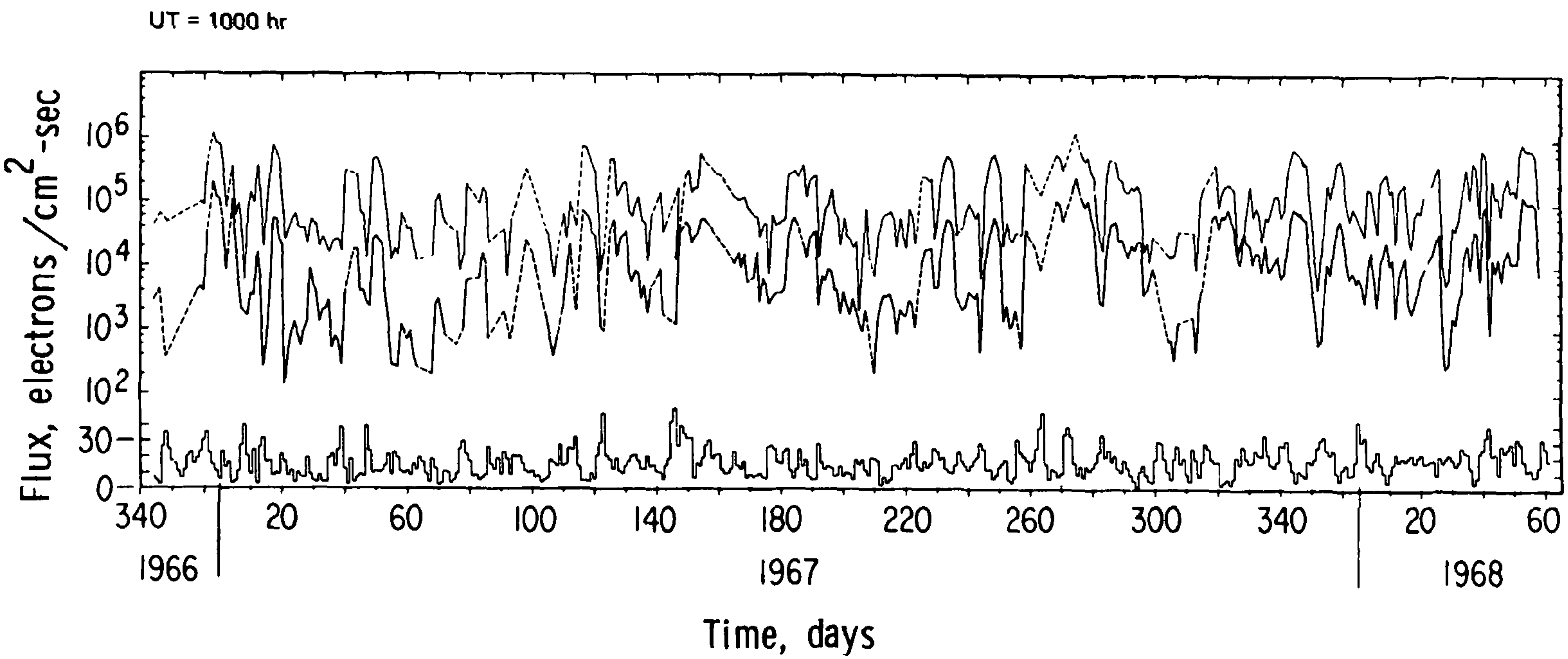

Figure 1.- Hourly averaged omnidirectional electrons for $E > 1.05$ MeV (upper) and $E > 1.9$ MeV (lower) observed from December 1966 to March 1968. Local time of all data is midnight. Daily sum of K_p is shown at the bottom of the figure. This figure was taken from Paulikas and Blake (ref. 8).

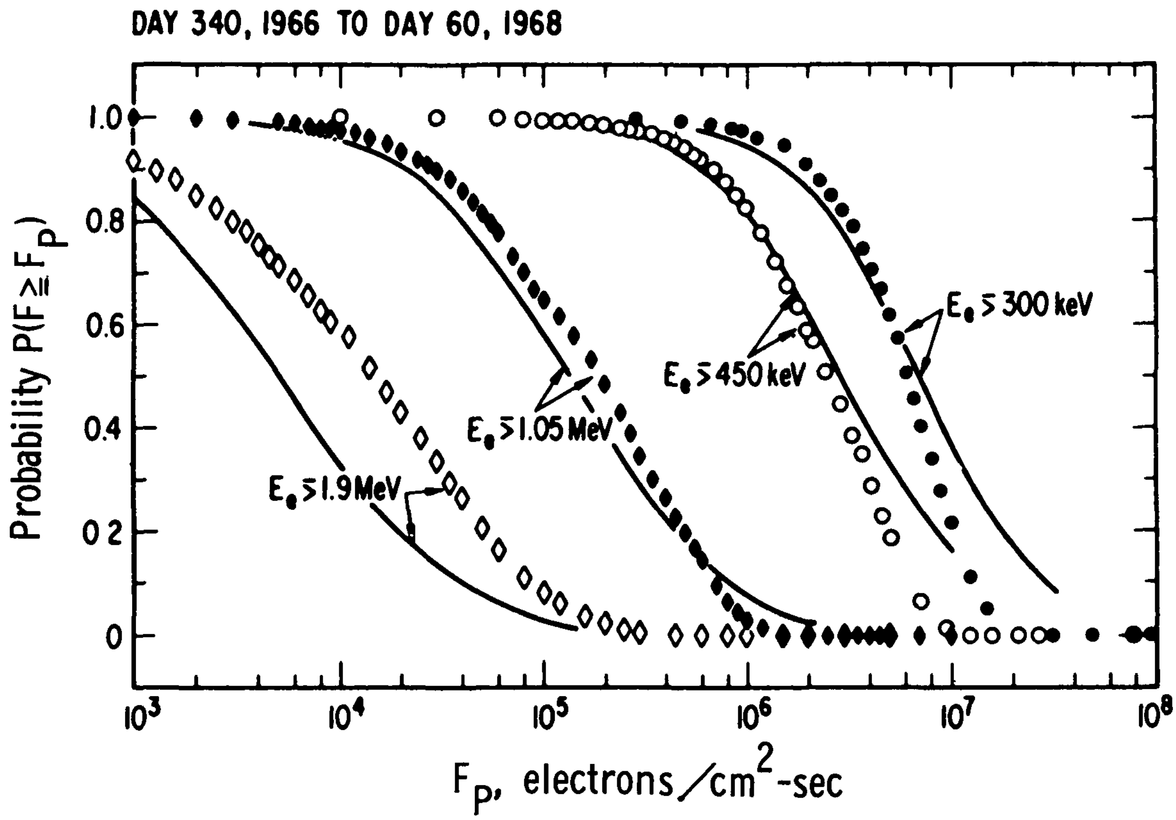

Figure 2.- The cumulative probability $P(F > F_P)$ as measured by Paulikas and Blake (ref. 8) in comparison with the AE3 model (curves). F denotes electron flux; F_P is the flux interval limit for probability P.

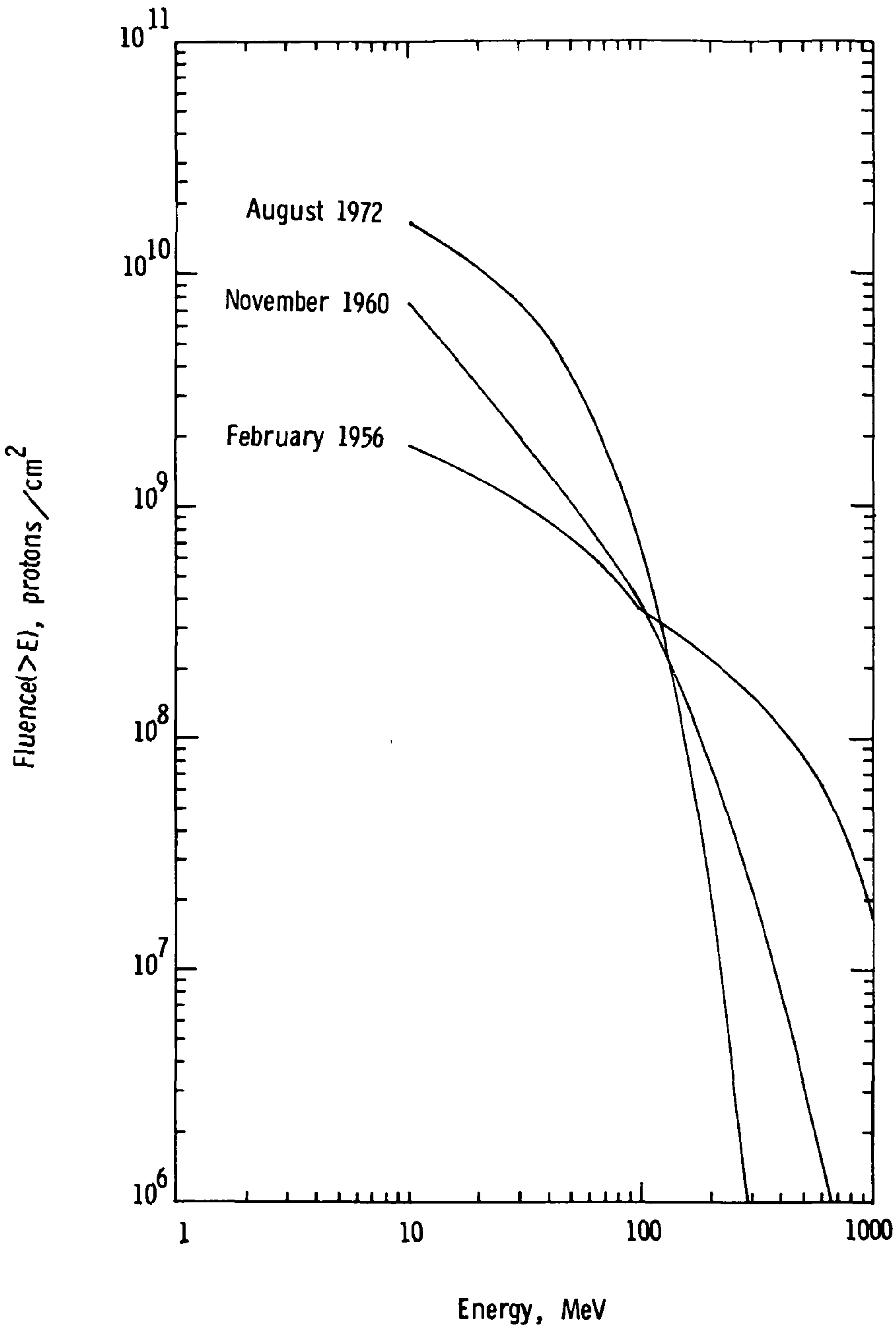

Figure 3.- Fluence spectra for three major solar particle events.

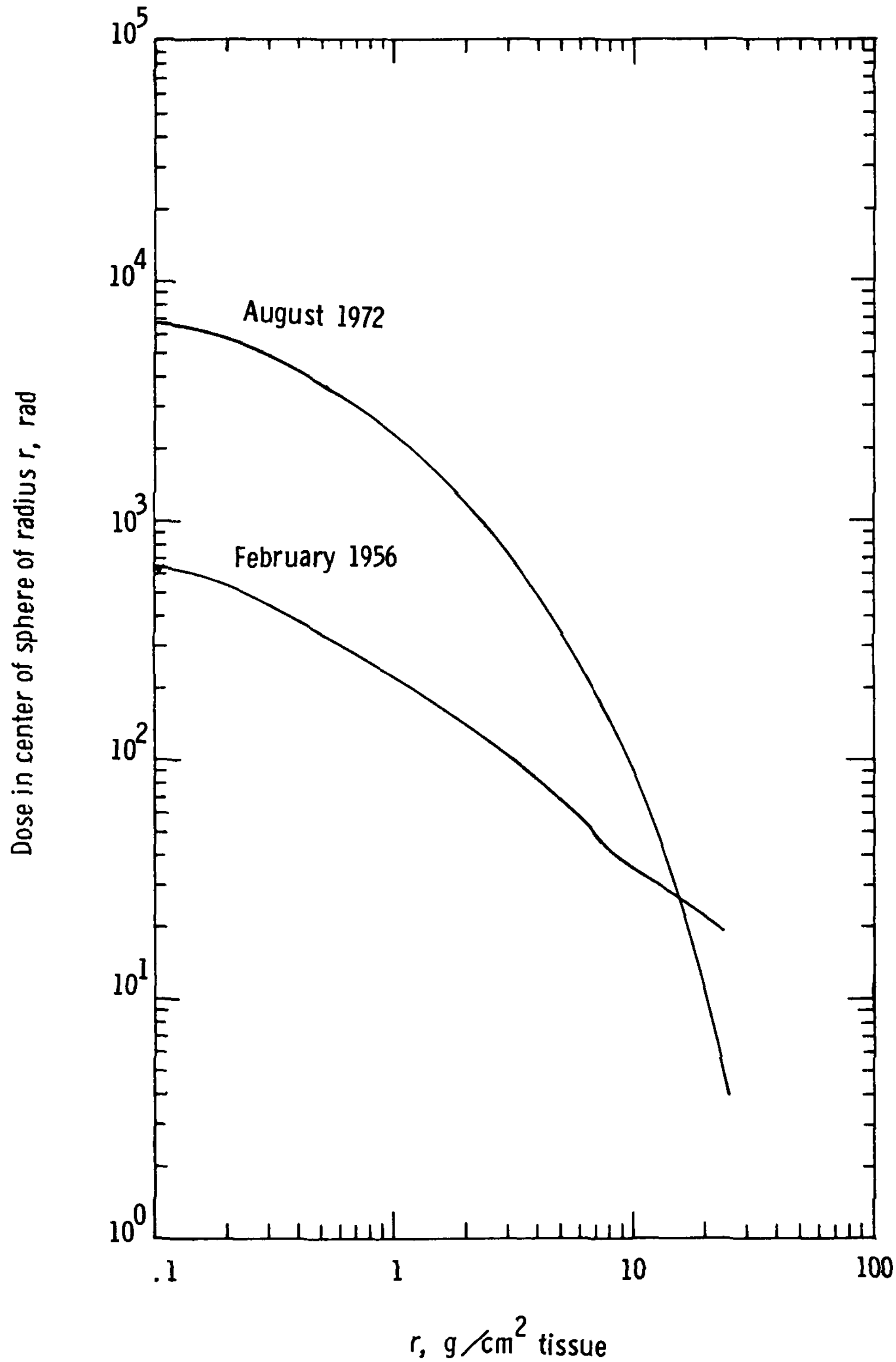

Figure 4.- Absorbed dose in a sphere produced by two major solar particle events.

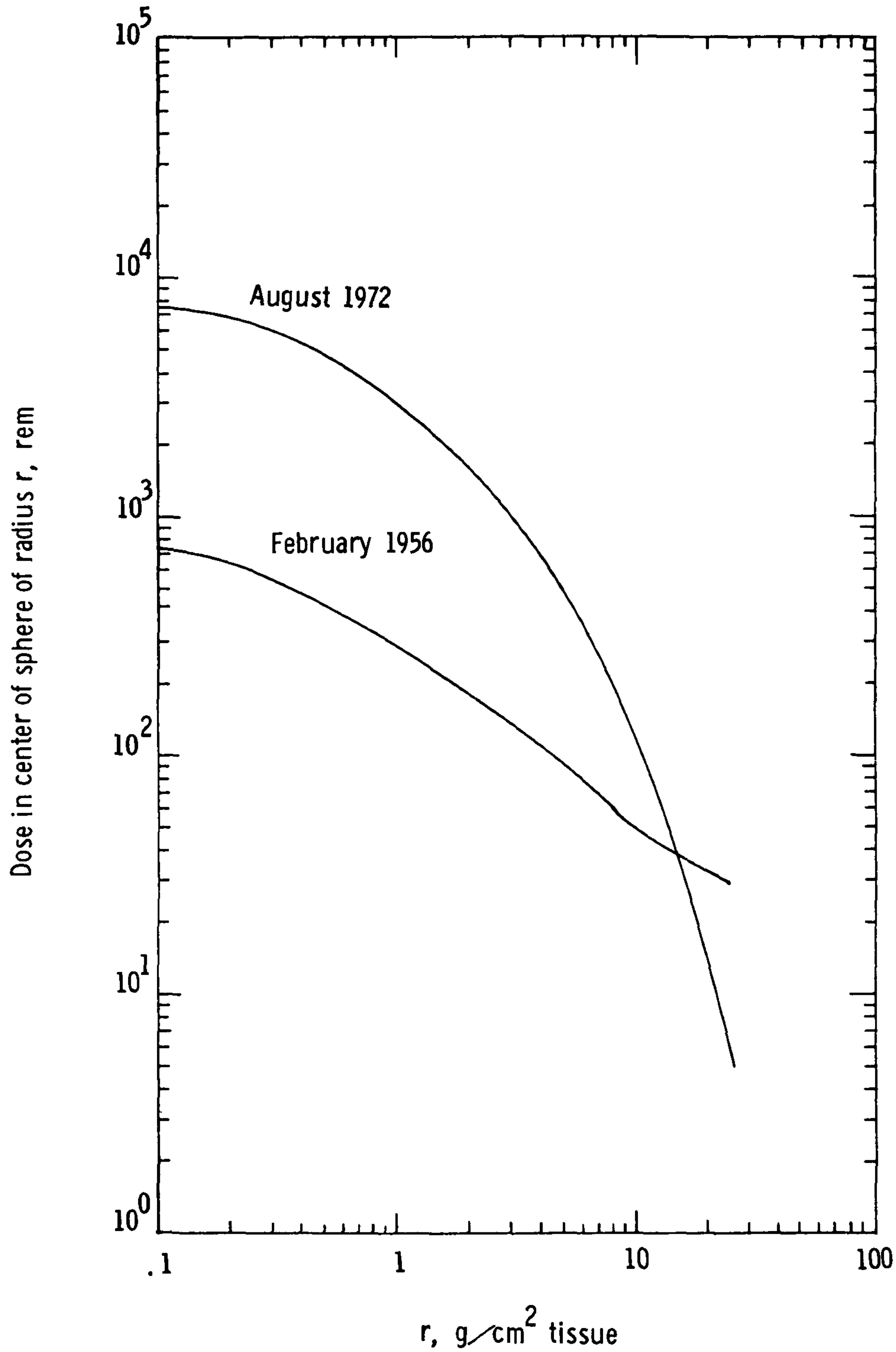

Figure 5.- Dose equivalent in a sphere produced by two major solar particle events.

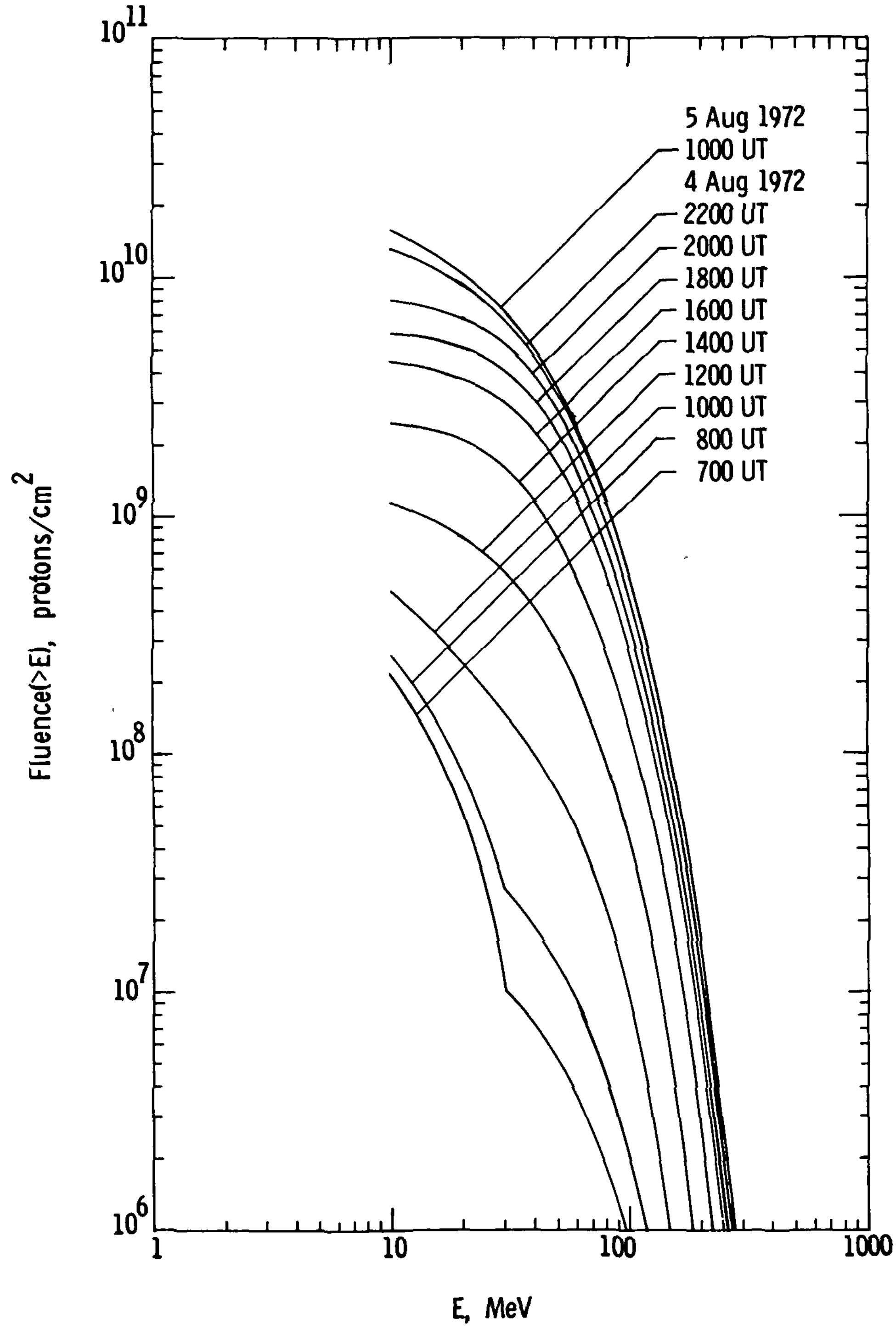

Figure 6.- Fluence from the August 1972 solar event as a function of time and energy.

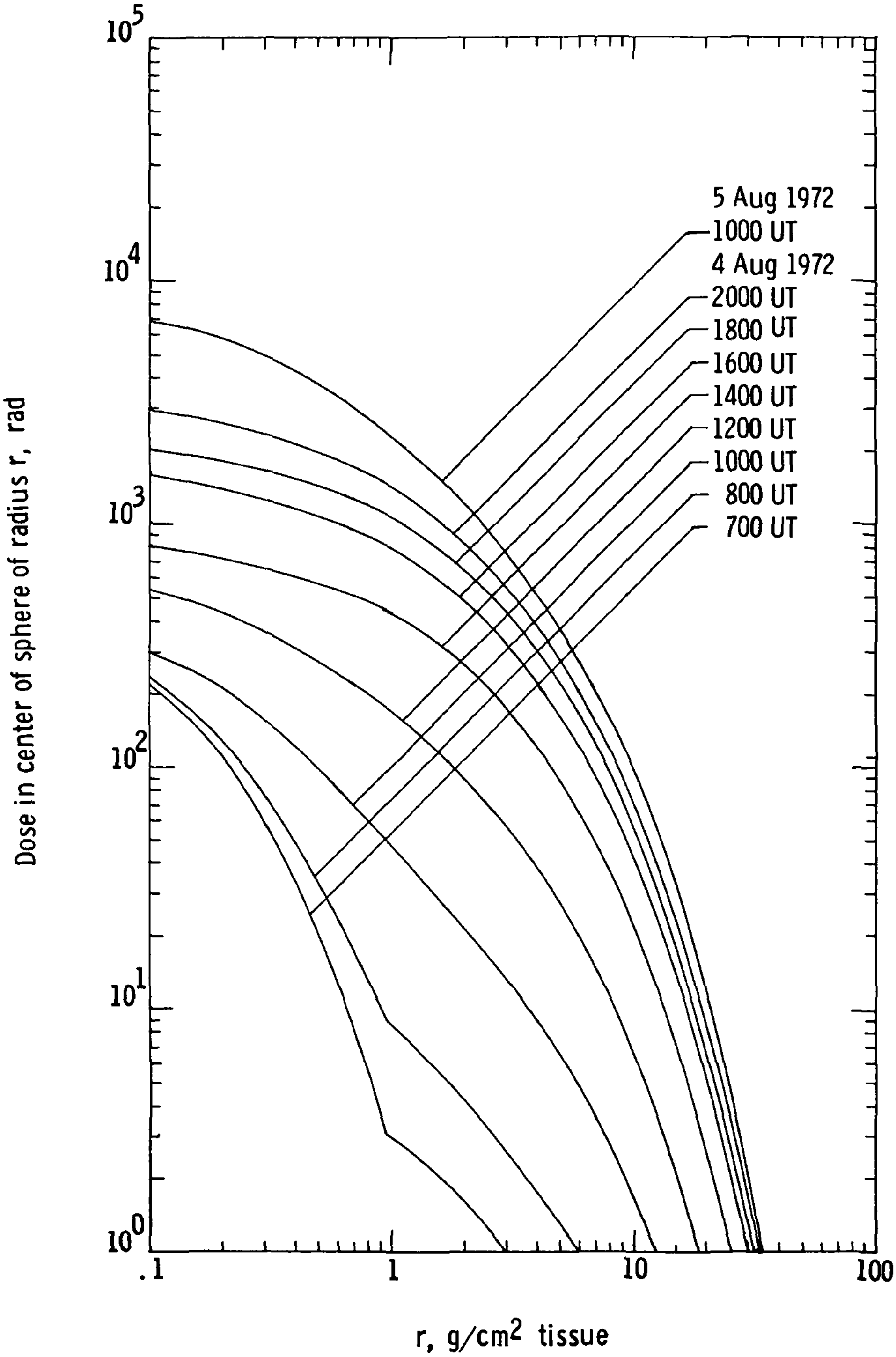

Figure 7.- Absorbed dose in a sphere as a function of time during August 4 and 5. The numbered hours are in units of UT.

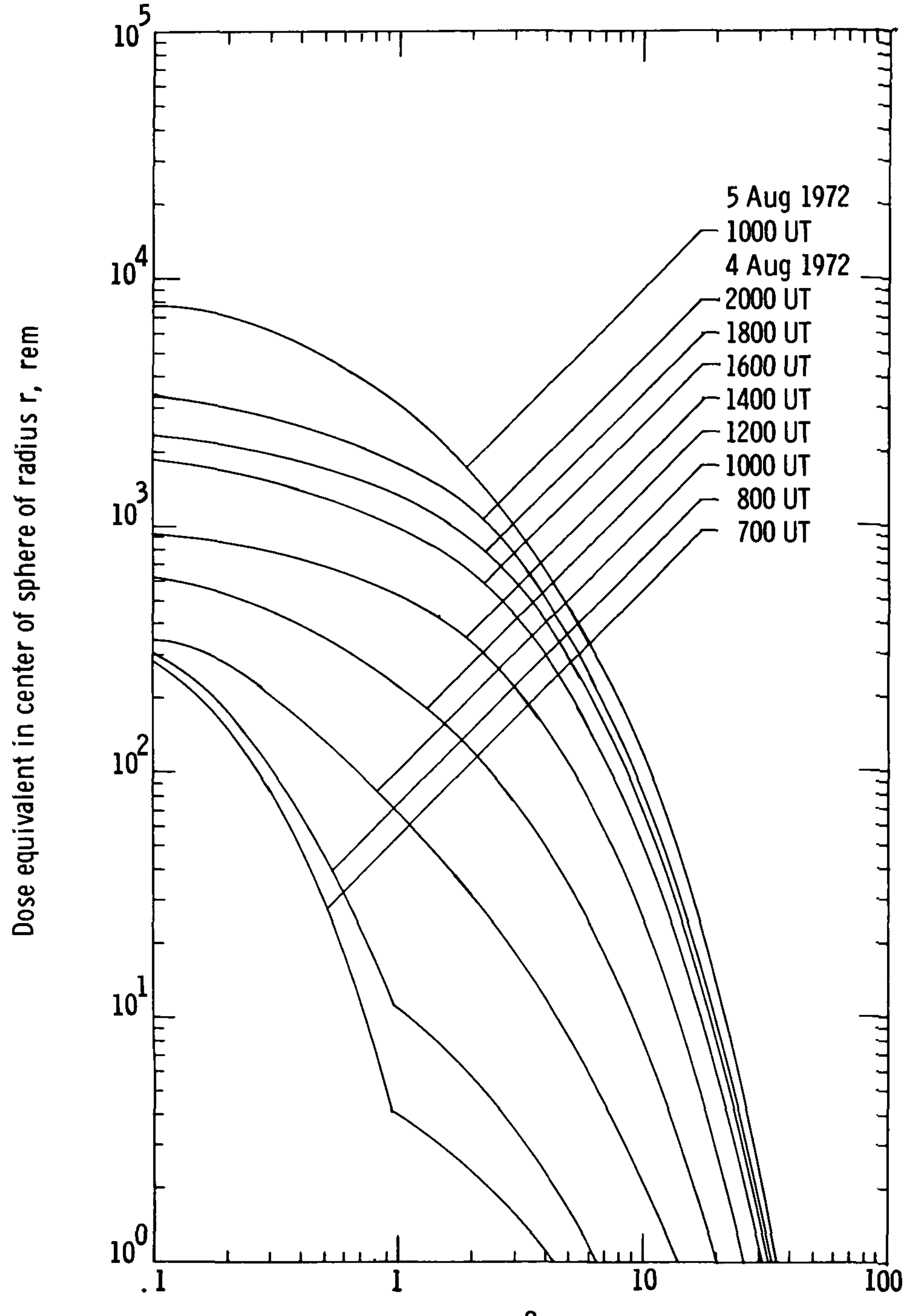

Figure 8.- Dose equivalent in a sphere as a function of time during August 4 and 5. The numbered hours are in units of UT.

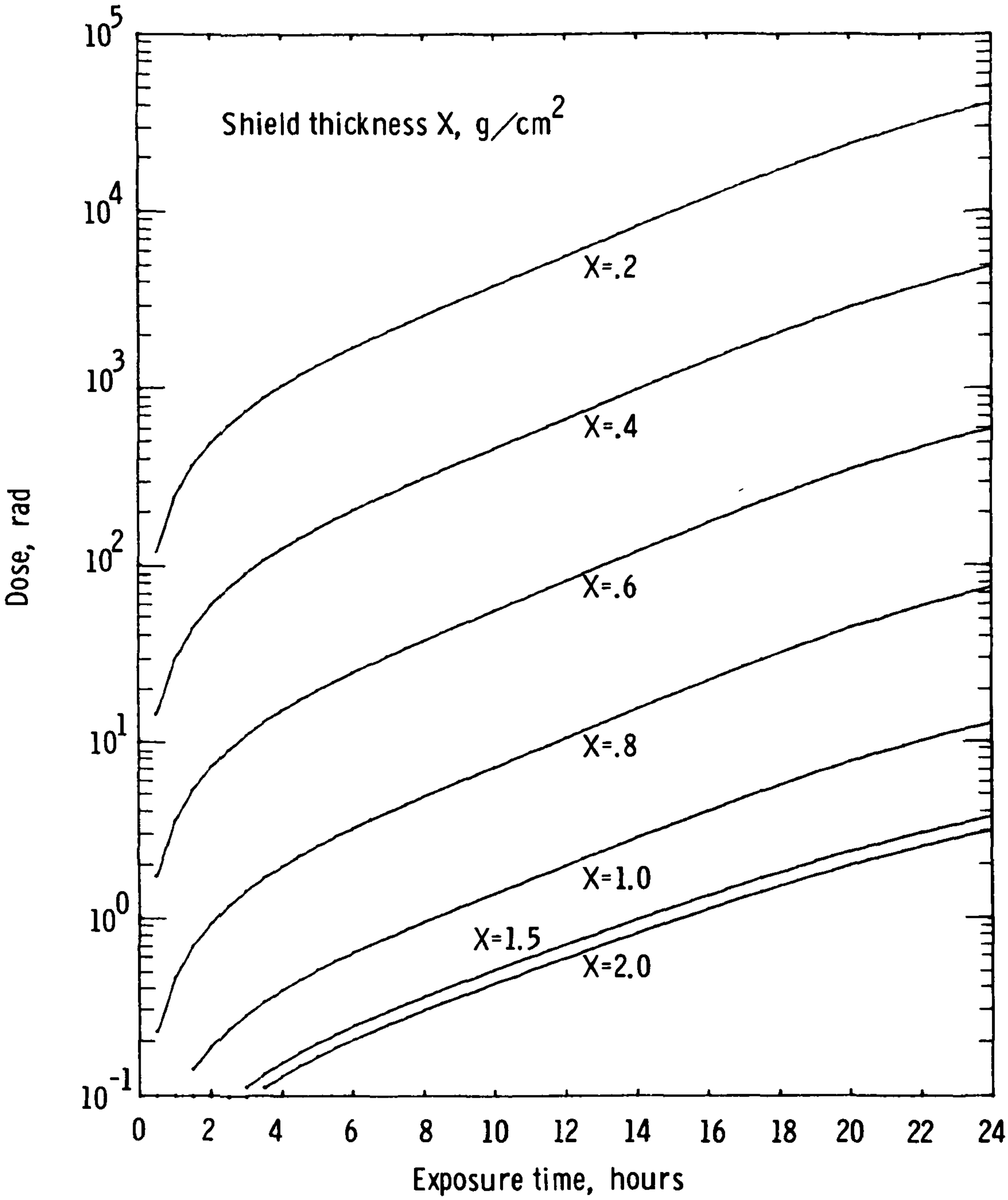

Figure 9.- Median doses as a function of exposure time (centered about 2300 local time) for several shield thicknesses.

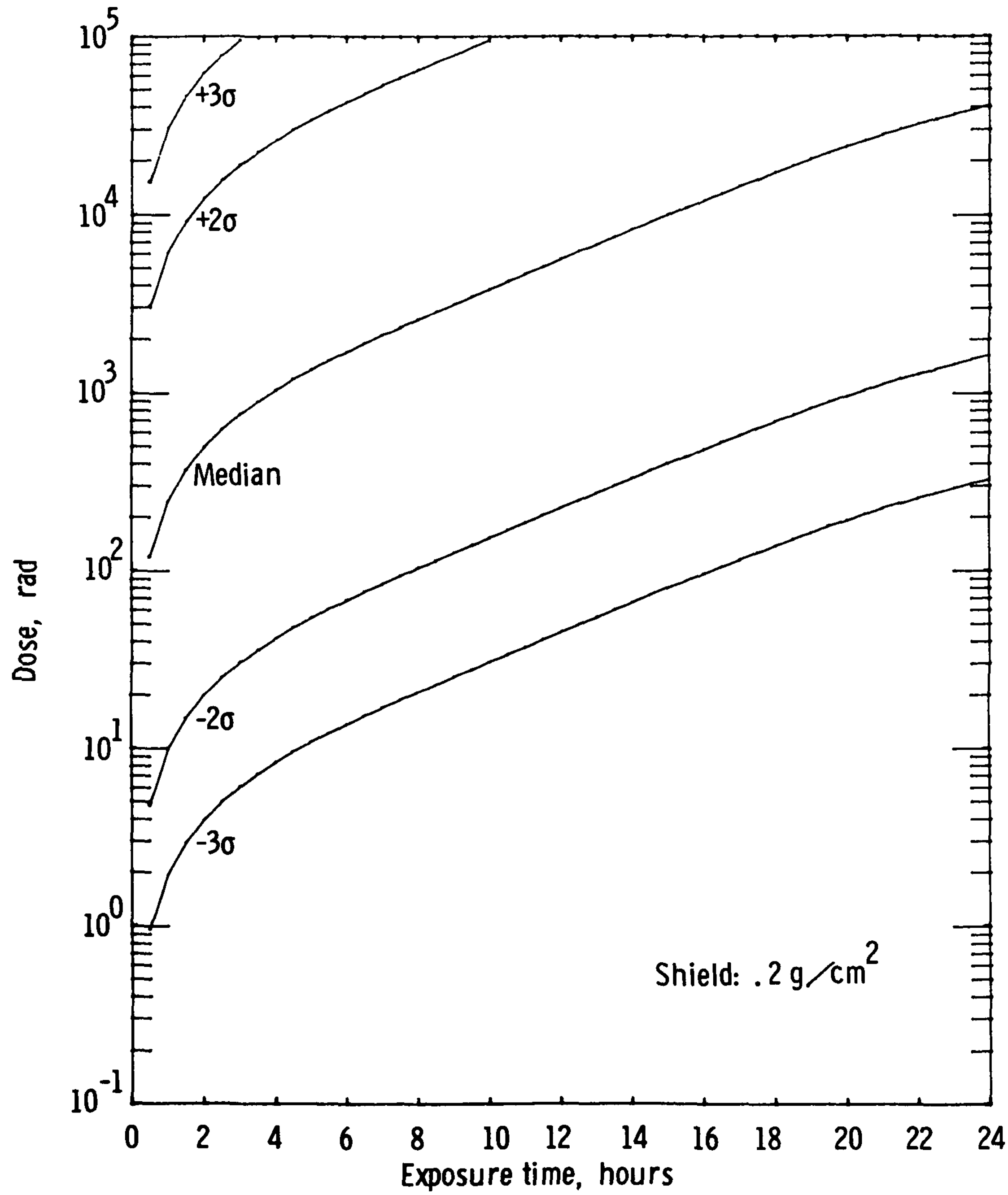

Figure 10.- Range of dose as a function of exposure time (centered about 2300 local time) for a shield of 0.2 g/cm^2 of aluminum.

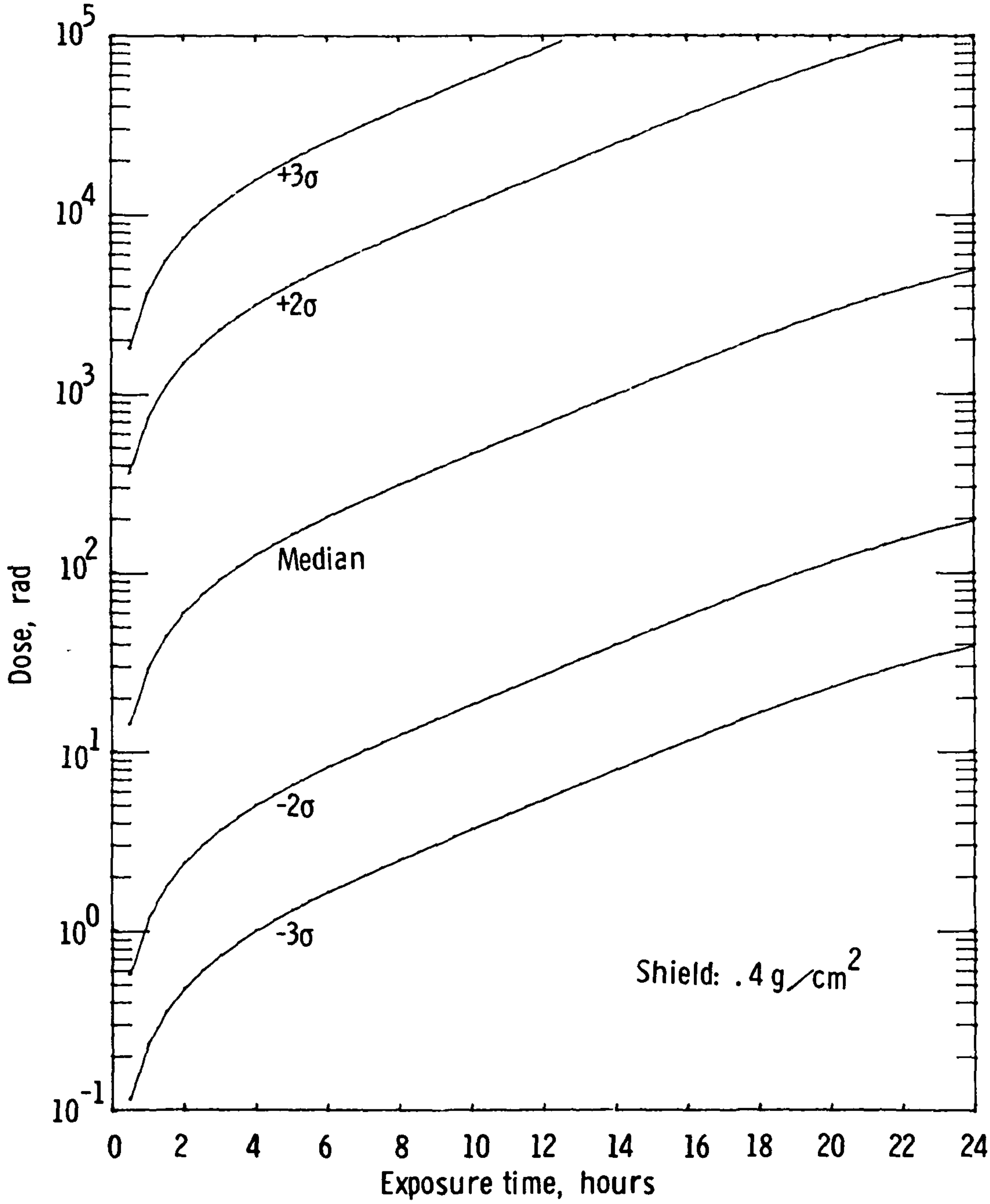

Figure 11.- Range of dose as a function of exposure time (centered about 2300 local time) for a shield of 0.4 g/cm² of aluminum.

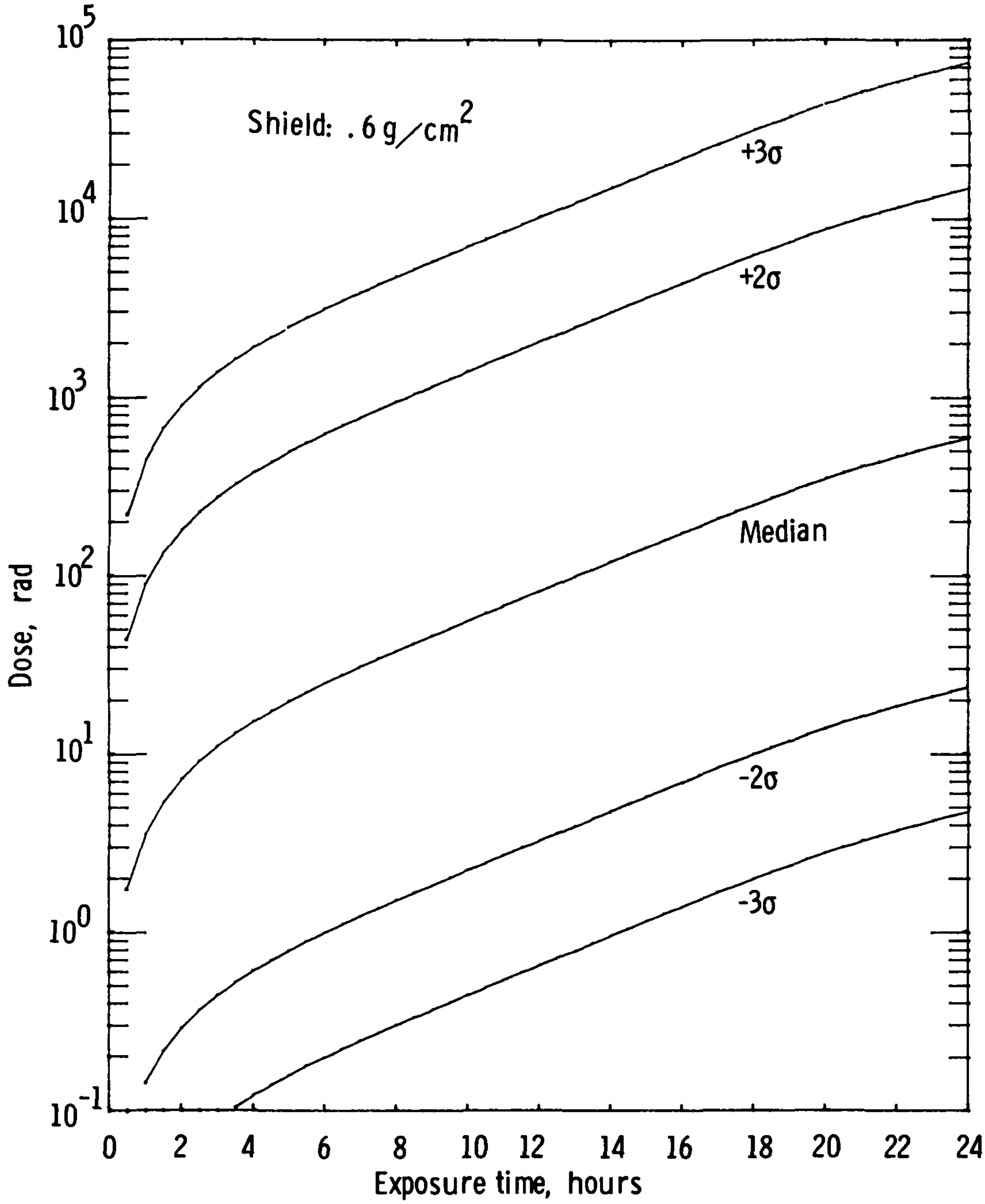

Figure 12.- Range of dose as a function of exposure time (centered about 2300 local time) for a shield of 0.6 g/cm^2 of aluminum.

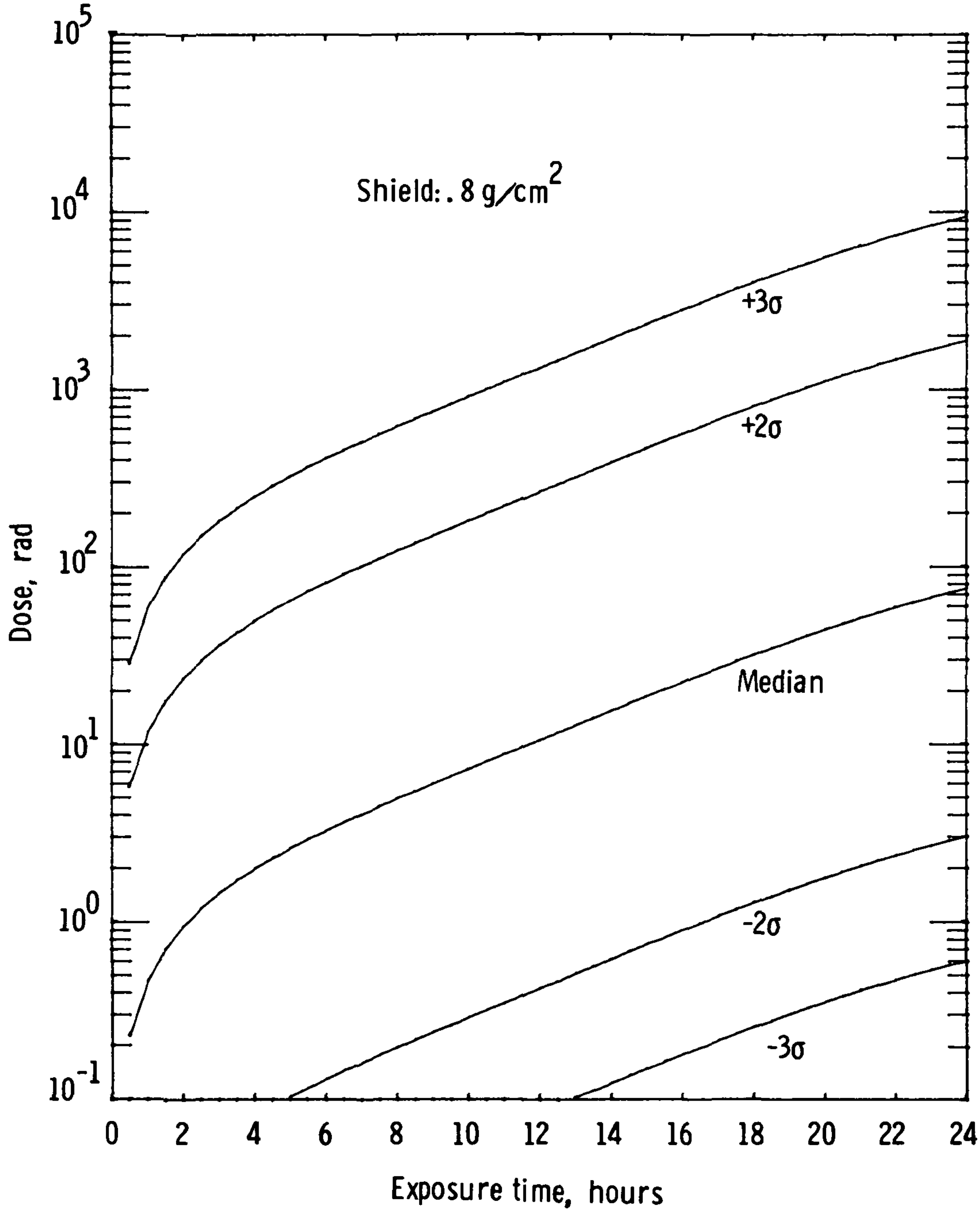

Figure 13.- Range of dose as a function of exposure time (centered about 2300 local time) for a shield of 0.8 g/cm^2 of aluminum.

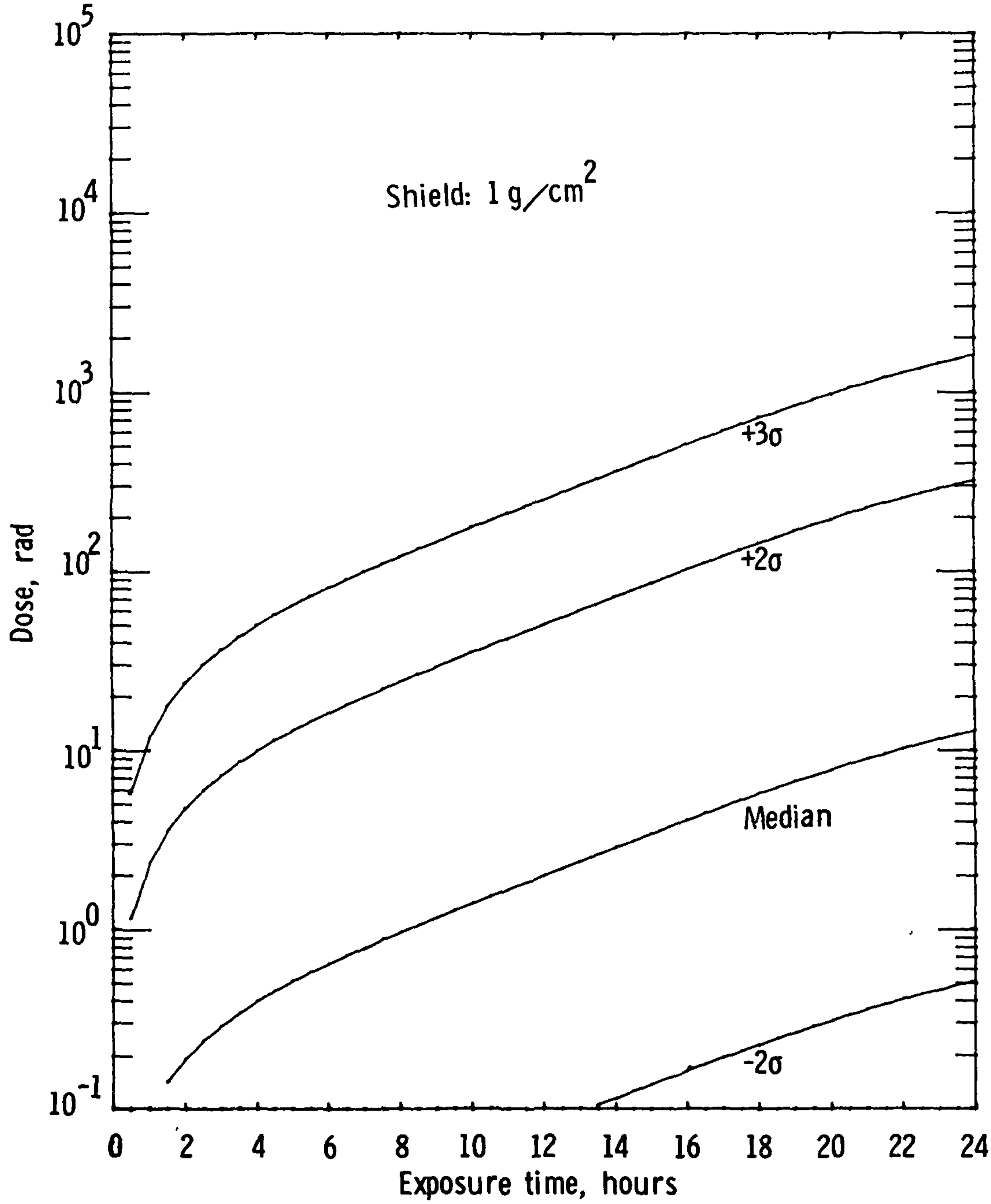

Figure 14.- Range of dose as a function of exposure time (centered about 2300 local time) for a shield of 1.0 g/cm^2 of aluminum.

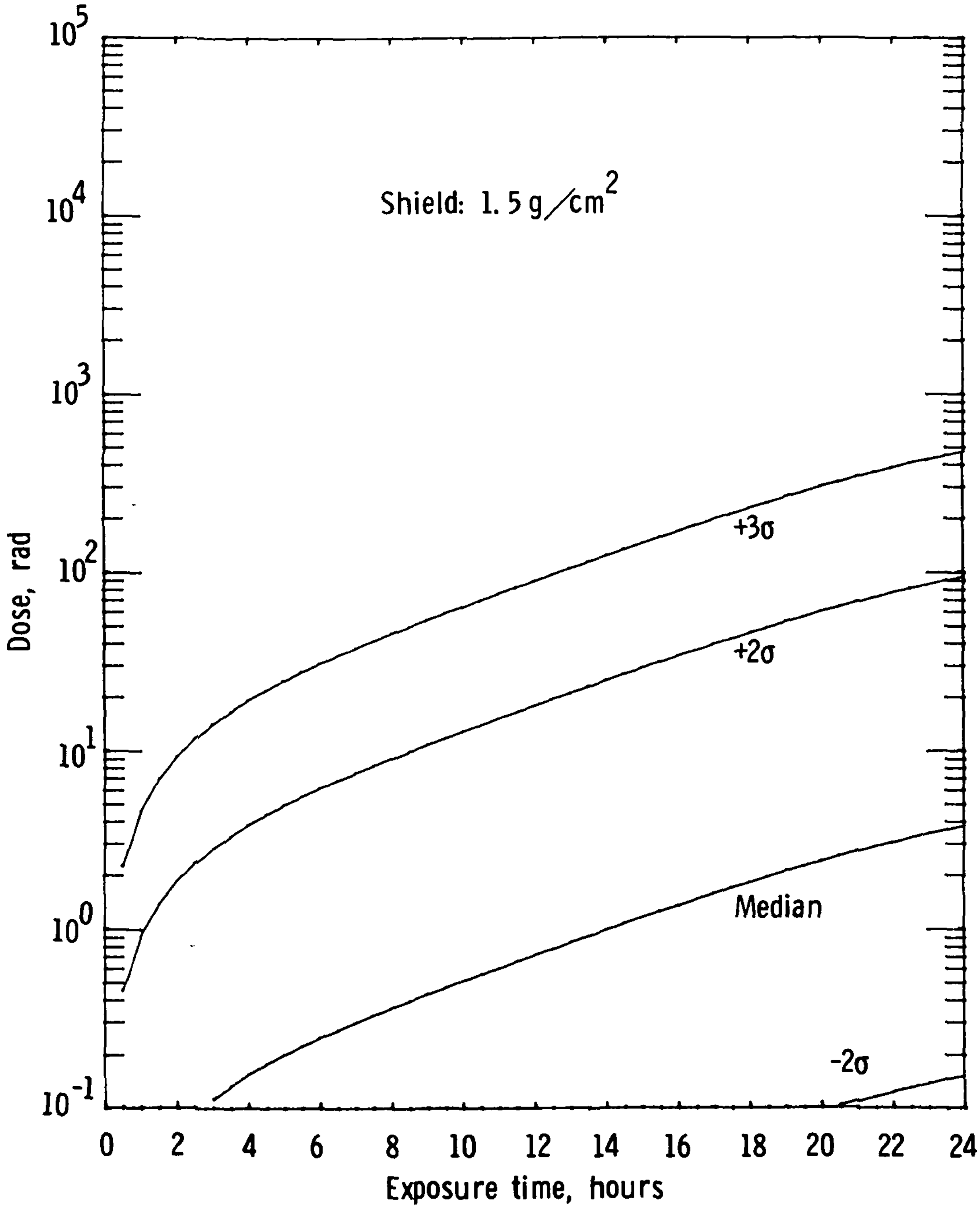

Figure 15.- Range of dose as a function of exposure time (centered about 2300 local time) for a shield of 1.5 g/cm^2 of aluminum.

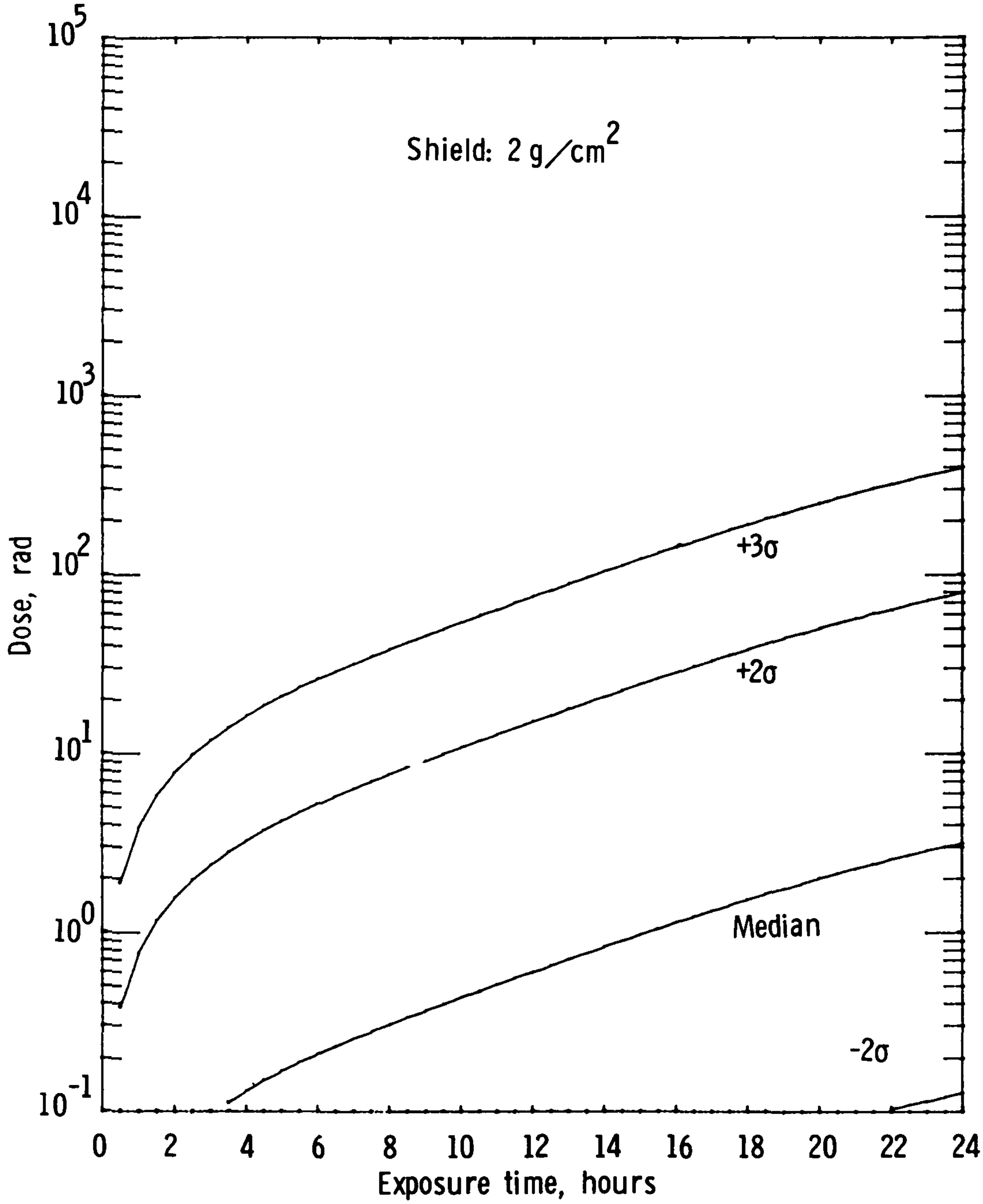

Figure 16.- Range of dose as a function of exposure time (centered about 2300 local time) for a shield of 2.0 g/cm^2 of aluminum.

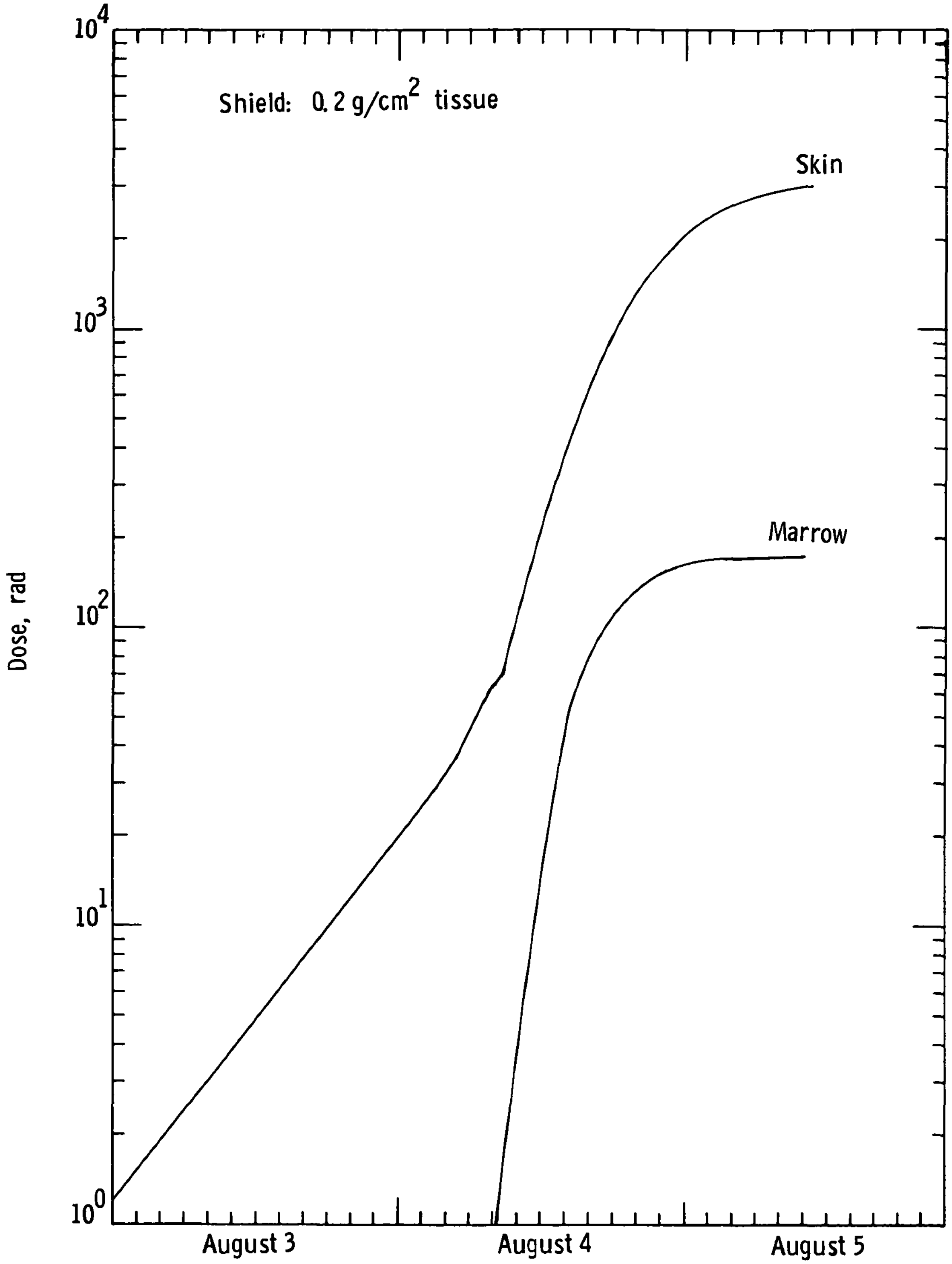

Figure 17.- Dose to an astronaut shielded by 0.2 g/cm^2 during August 1972.

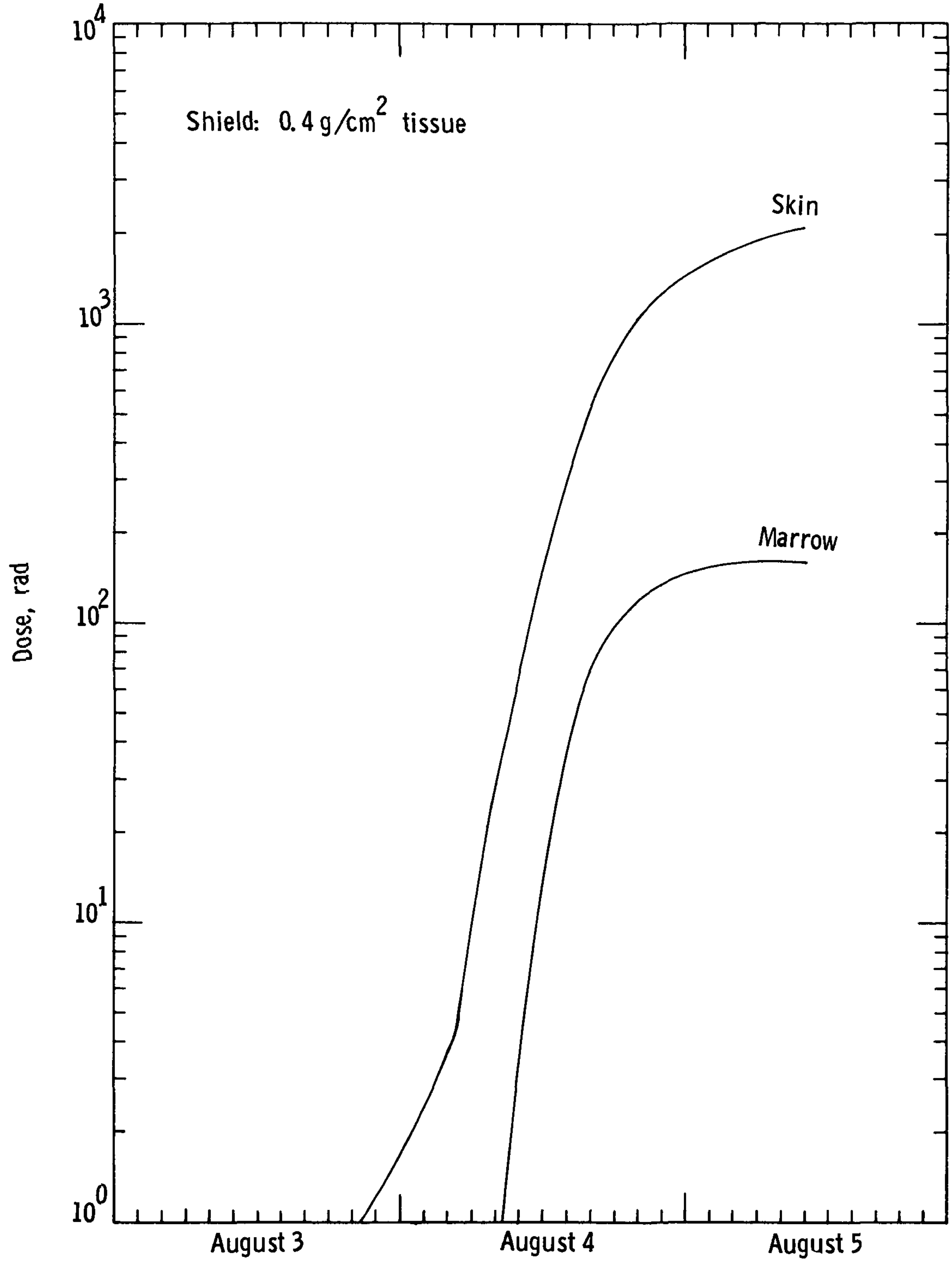

Figure 18.- Dose to an astronaut shielded by 0.4 g/cm^2 during August 1972.

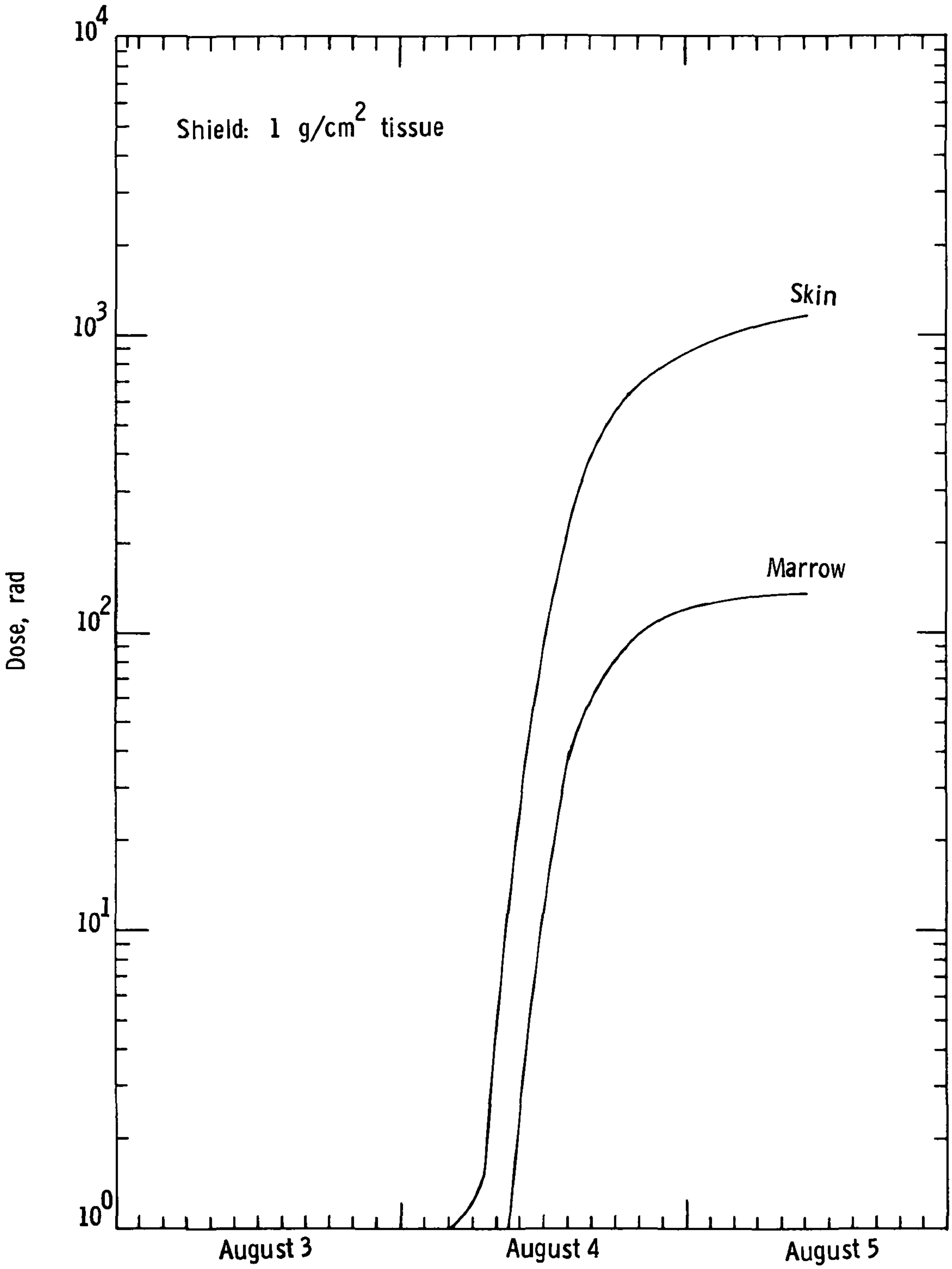

Figure 19.- Dose to an astronaut shielded by 1.0 g/cm^2 during August 1972.

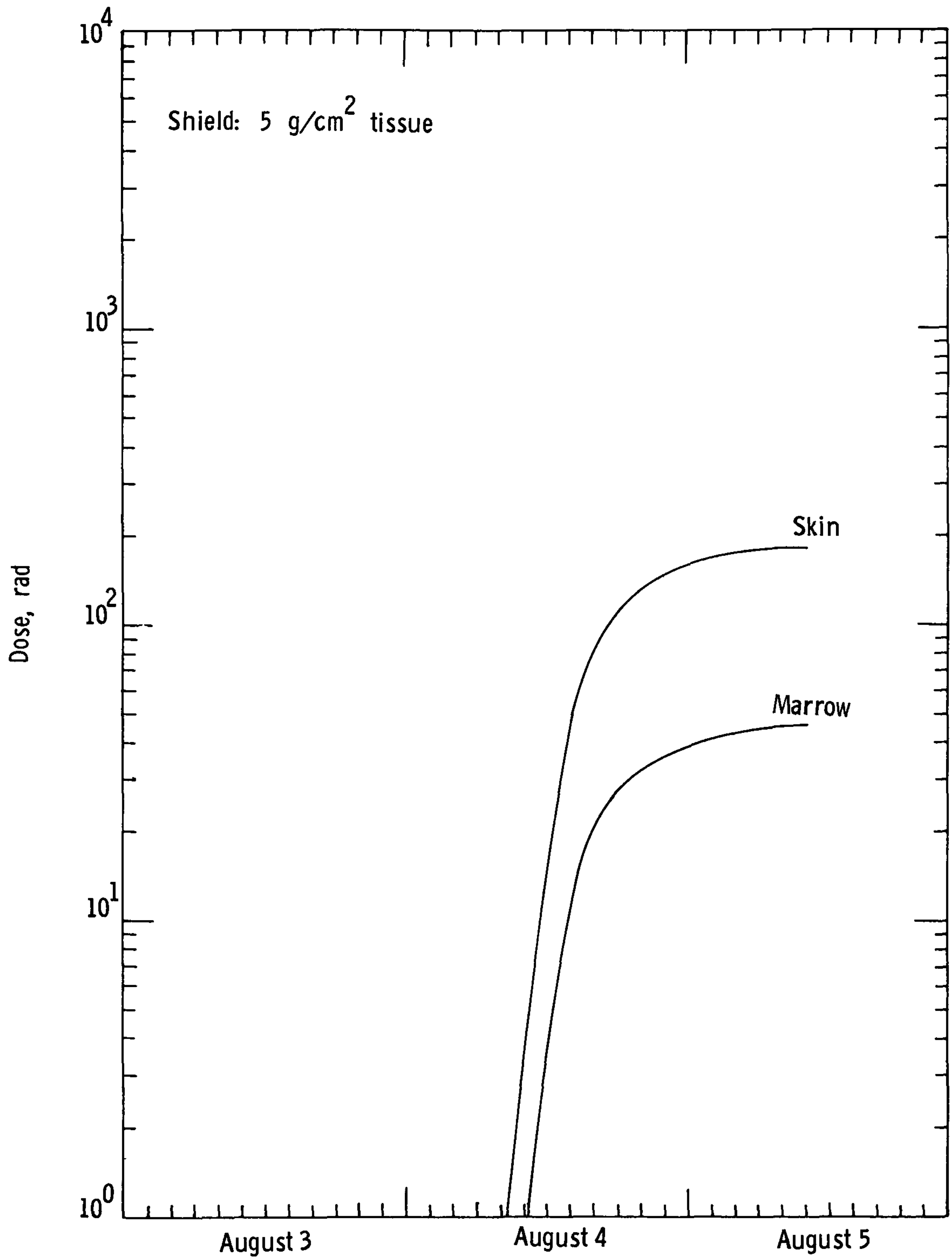

Figure 20.- Dose to an astronaut shielded by 5.0 g/cm^2 during August 1972.

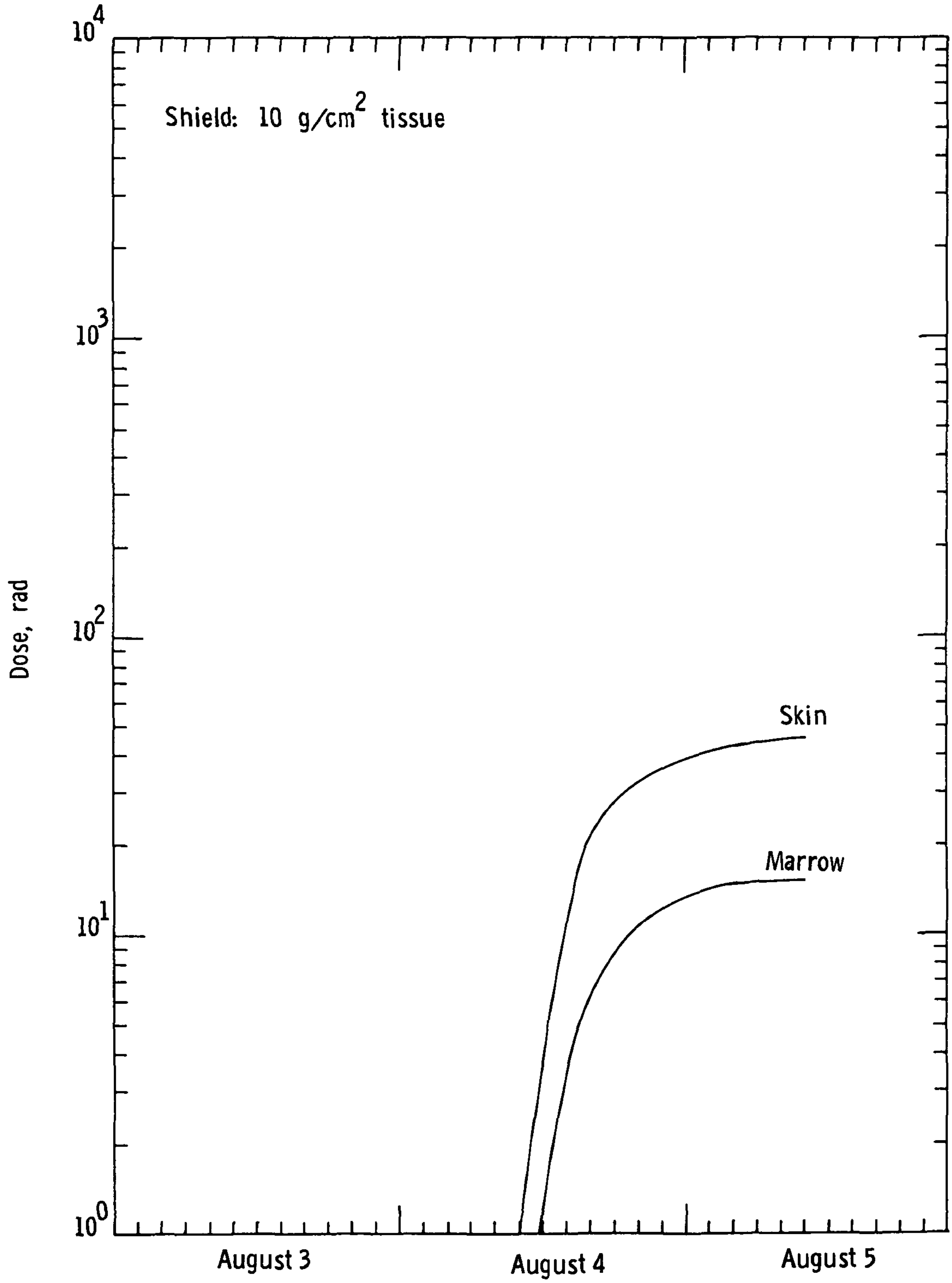

Figure 21.- Dose to an astronaut shielded by 10.0 g/cm^2 during August 1972.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof"

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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