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MEASURED AND CALCULATED NEUTRON SPECTRA AND DOSE EQUIVALENT RATES AT HIGH ALTITUDES; RELEVANCE TO SST OPERATIONS AND SPACE RESEARCH

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16. Abstract

Results of the NASA Langley-New York University high-altitude radiation study are presented. Measurements of the absorbed dose rate and of secondary fast neutrons (1 to 10 MeV energy) during the years 1965 to 1971 are used to determine the maximum radiation exposure from galactic and solar cosmic rays of supersonic transport (SST) and subsonic jet occupants. The maximum dose equivalent rates that the SST crews might receive turn out to be 13 to 20 percent of the maximum permissible dose rate (MPD) for radiation workers (5 rem/yr). The exposure of passengers encountering an intense giant-energy solar particle event could exceed the MPD for the general population (0.5 rem/yr), but would be within these permissible limits if in such rare cases the transport descends to subsonic altitude; it is in general less than 12 percent of the MPD. By Monte Carlo calculations of the transport and buildup of nucleons in air for incident proton energies E of 0.02 to 10 GeV, the measured neutron spectra were extrapolated to lower and higher energies and for galactic cosmic rays were found to continue with a relatively high intensity (small slope $\approx E^{-1.2}$) to energies >400 MeV, in a wide altitude range. This condition, together with the measured intensity altitude profiles of fast neutrons, revealed that the biologically important fast and energetic neutrons penetrate deep into the atmosphere and contribute approximately 50 percent of the dose equivalent rates at SST and present subsonic jet altitudes. The worldwide measurements and the extension of the neutron calculations to higher altitudes and thermal energies by New York University (the former also by Oak Ridge National Laboratory) led to new determinations of the leakage rates of energetic neutrons out of the atmosphere, some of which decay to protons that remain trapped in the Van Allen belt, and of the time-dependent global radiocarbon production rate (fossil dating). It was also discovered that during certain Forbush decreases, the decrease and recovery of the low-energy cosmic rays lag behind those of the high-energy cosmic rays. Unsolved problems are briefly discussed such as the biological effects of low doses of energetic neutrons and the reactions of the heavier nuclei with matter, which are relevant to a more complete understanding of the radiation environments and their effects in high altitude and space vehicles, and of the cosmic rays themselves.

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RELEVANCE TO SST OPERATIONS

AND SPACE RESEARCH

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SUMMARY

Results of the NASA Langley-New York University high-altitude radiation study are presented. Measurements of the absorbed dose rate and of secondary fast neutrons (1 to 10 MeV energy) during the years 1965 to 1971 are used to determine the maximum radiation exposure from galactic and solar cosmic rays of supersonic transport (SST) and subsonic jet occupants. The maximum dose equivalent rates that the SST crews might receive turn out to be 13 to 20 percent of the maximum permissible dose rate (MPD) for radiation workers (5 rem/yr). The exposure of passengers encountering an intense giant-energy solar particle event could exceed the MPD for the general population (0.5 rem/yr), but would be within these permissible limits if in such rare cases the transport descends to subsonic altitude; it is in general less than 12 percent of the MPD. By Monte Carlo calculations of the transport and buildup of nucleons in air for incident proton energies E of 0.02 to 10 GeV, the measured neutron spectra were extrapolated to lower and higher energies and for galactic cosmic rays were found to continue with a relatively high intensity (small slope $\approx E^{-1.2}$) to energies >400 MeV, in a wide altitude range. This condition, together with the measured intensity altitude profiles of fast neutrons, revealed that the biologically important fast and energetic neutrons penetrate deep into the atmosphere and contribute approximately 50 percent of the dose equivalent rates at SST and present subsonic jet altitudes. The worldwide measurements and the extension of the neutron calculations to higher altitudes and thermal energies by New York University (NYU) (the former also by Oak Ridge National Laboratory (ORNL)) led to new determinations of the leakage rates of energetic neutrons out of the atmosphere, some of which decay to protons that remain trapped in the Van Allen belt, and of the time-dependent global radiocarbon production rate (fossil dating). It was also discovered that during certain Forbush decreases, the decrease and recovery of the low-energy cosmic rays lag

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behind those of the high-energy cosmic rays. Unsolved problems are briefly discussed such as the biological effects of low doses of energetic neutrons and the reactions of the heavier nuclei with matter, which are relevant to a more complete understanding of the radiation environments and their effects in high altitude and space vehicles, and of the cosmic rays themselves.

I. INTRODUCTION

Supersonic commercial airplanes of the near future will cruise at altitudes between 18 and 21 km (60 000 and 68 000 ft). The atmosphere above these altitudes contains only about 5 to 7 percent ($\approx$50 to 70 g/cm^2) of the mass of the Earth's atmosphere ($\approx$1033 g/cm^2 at sea level), and it protects the occupants of the supersonic transport (SST) against soft extraterrestrial radiations such as auroral or belt electrons and their secondary X-rays.

This thin air layer is not sufficient, however, to protect against the energetic galactic cosmic rays and their penetrating secondaries produced within the atmosphere or against energetic solar cosmic rays and their secondaries. Although other penetrating natural radiations, such as relativistic electron precipitation, are observed and energetic neutrons coming directly from the Sun are suspected, present indications are that at SST altitudes they produce doses substantially less than those produced by galactic and solar cosmic rays. This paper is therefore based on the present understanding that the exposure from natural radiation encountered at SST altitudes is mainly due to the energetic low-level galactic cosmic rays and the transient solar cosmic rays; the latter, although lower in energy, are in some cases orders of magnitude more intense than the galactic cosmic rays.

The always present galactic cosmic rays are actually particles — mostly protons, α-particles (helium nuclei), and some heavier nuclei — of high energy (averaging a few GeV/nucleon) but of low intensity. The transient solar cosmic rays are protons, α-particles, and a few heavier nuclei in varying proportions (for example, the ratio of α-particles to protons may be as high as 1) which are accelerated at the Sun to energies up to >10 GeV during some solar flare events. Although solar events producing particles of energy <1 GeV are relatively frequent during solar active years, the so-called giant energy events, that is, events of higher energy (in the multi GeV range) and of high intensity, which are one of the main subjects of this paper, are rather rare.

Solar and galactic cosmic rays are not substantially attenuated, but are rather modified and multiplied, by the upper 100 g/cm^2 of air if their energy is in the GeV range. For example, the galactic cosmic rays penetrate deep into the atmosphere either as primaries or, especially, as secondary cascade nucleons, the latter including biologically

effective energetic neutrons which reach their peak intensity just about at SST altitudes. Of the medium- and low-energy solar cosmic ray primaries, only a few penetrate to these altitudes. However, they also produce biologically effective secondaries such as neutrons, which penetrate relatively freely to greater atmospheric depths and are the main or sole contributions of medium- and low-energy solar cosmic rays to the dose equivalent rate at SST altitudes.

There is shielding from galactic cosmic ray primaries by the interplanetary magnetic fields — especially during years of greatest solar activity (solar modulation) — and from both solar cosmic rays and galactic cosmic rays by the Earth's magnetic field. Because of the Earth's magnetic field, the intensity of the galactic cosmic rays varies from a maximum at the magnetic poles to a minimum at the magnetic equator. The variations of the ionization produced by charged primary and secondary components within the atmosphere were measured by Neher and Anderson (ref. 1) during the last solar cycle (1954 to 1964), using argon-filled steel-walled ionization chambers. (Measurements with these chambers do not include the ionization by biologically important recoil protons produced by neutrons in tissue.) There are also strong latitude variations of the radiation levels from the solar cosmic rays, which limit these radiations mainly to the polar regions (geomagnetic latitudes greater than 55°) for most events. The analyses of the latitude and longitude variations are complicated because the solar cosmic rays are not always isotropic during the early phases of the events, and the geomagnetic field is often disturbed, and, as a result, allows particles normally excluded to enter the Earth's atmosphere. The directionality of the "prompt" solar cosmic rays produces the largest effects in so-called "impact" zones. (See ref. 2.)

The galactic cosmic rays (of which roughly 85 percent are protons, 13.5 percent are α-particles, and 1.5 percent are heavier nuclei) have an average energy E of 3 to 4 GeV per nucleon, the highest energies exceeding 10^{10} GeV and the intensities decreasing as $E^{-2.7}$. As mentioned before, the total flux is low, being about 0.53 nucleon/cm^2-sec-sr at the galactic cosmic ray maximum (about 1 year after sunspot minimum). These fluxes produce an absorbed dose rate of about 1 mrad/hr at high altitudes in high latitudes. The flux decreases to 0.27 nucleon/cm^2-sec-sr at galactic cosmic ray minimum.

The solar cosmic rays are ejected during some, but not all, solar flare events. Such events are referred to as solar proton events. Many of these solar proton events produce only low-energy particles, that is, particles with energies less than 50 MeV. Less frequent are moderate energy events with particles of measurable intensity in the 100 MeV to 1 GeV range. Extremely intense events of this kind were encountered on Earth during the last solar cycle (cycle 19) on May 12, 1959, and July 10, 14, and 16, 1959, and on November 12 and 15, 1960. Their total number may have been 8 during the 11 years of cycle 19. Very rare are the so-called "giant" energy events of high intensity, for example, the event of February 23, 1956, when measurable intensities of particles with

energies greater than 15 GeV were observed and indicated an astonishing potential of the Sun to accelerate particles to high energies. For the first hour of this event, a flux of 400 to 800 protons/cm^2-sec-sr with energies greater than 600 MeV is estimated, which is about three orders of magnitude greater than the galactic cosmic ray background. During the early phases of this event, the ground-level neutron monitor counts in New Hampshire increased by 3600 percent. In contrast, in the most intense medium energy event of cycle 19 (November 12, 1960), the ground-level monitors increased to only 225 percent.

The solar cosmic ray intensities vary greatly from event to event, as do also the energy spectra. Furthermore, both of these characteristics change as a given event progresses. Typically, the hardest spectra occur during the onset of the event; these are the previously mentioned prompt particle spectra. In the case of the February 1956 event, the intensity of GeV particles attained its maximum in 20 minutes and then decayed with a half-life of about 1 hour. If the prompt particles arrive anisotropically, isotropy is approached after 1/2 hour to a few hours. The maximum flux of lower energy primaries in the 100 MeV range and below is usually reached after several hours and the flux decays slowly during the following 1 or 2 days.

Both the galactic cosmic rays and the solar cosmic rays lose energy in the atmosphere because of ionization, and they also enter into nuclear interactions with air atoms. The heavier nuclei are slowed by ionization faster than the protons. The nuclear interactions of both generally produce a multitude of secondary particles (protons, neutrons, deuterons, α-particles, heavy nuclei, γ-rays, mesons, a few strange particles, and electron-photon cascades). Many of the secondary nucleons have sufficient energy to enter into further nuclear reactions. In this way several generations of secondaries are built up, especially nucleon cascades, which extend to sea level if the primaries have energies greater than 500 MeV/nucleon.

The problem is to assess the biological dose, or dose equivalent in tissue, of this mixture of primary and secondary particles produced by galactic cosmic rays and energetic solar cosmic rays.

The particles whose biological effects are least known quantitatively are the heavy primaries and the energetic heavy nuclei produced by the nuclear collisions of primaries with air atoms. Very few of the heavier primaries or energetic heavy collision products reach the SST cruise altitude of the near future (20 km or 65 000 ft), because of ionization loss and breakup in nuclear interactions in the upper atmosphere. More important, because of their much larger number, are the energetic neutrons (0.1 to 500 MeV) which penetrate the air relatively freely. In tissue, however, they produce densely ionizing recoil nuclei (mostly proton recoils) and "star" prongs (mainly consisting of evaporation particles) which are biologically more effective than energetic lightly ionizing particles.

There is further star production in tissue due to high-energy protons and α-particles. The primary protons and α-particles ionize only lightly along their paths.

References 3 to 14 present studies to determine the dose equivalents at high altitudes from cosmic ray measurements and nuclear interaction data. In reference 14, in particular, the contribution of galactic heavy nuclei at SST altitudes is discussed in detail.

The main experimental bases for these estimates are the measurements of Neher and Anderson with argon-filled ionization chambers and the studies of stars with conventional nuclear emulsions (refs. 3 and 15) from which stars in tissue were theoretically derived. Since neither of these sensors is tissue equivalent, the estimates are of uncertain accuracy. The contribution of neutrons to the dose equivalent in tissue is especially uncertain. There existed only few direct measurements of high-energy neutrons and these were made mostly at lower altitudes or at medium latitudes. (See refs. 16 to 19.) Estimates of dose equivalents from galactic cosmic rays in reference 13 derived from measurements of Haymes (ref. 18) include the effect of neutrons with energies of 1 to 14 MeV only and do not take into account the large contribution from neutrons in the energy ranges of 0.1 to 1 MeV and greater than 14 MeV. (See tables 1 and 5 of ref. 13.)

Also, theoretical calculations of the neutron spectra within the atmosphere (for example, refs. 13 and 20 to 22) which were used in these earlier estimates differ to a considerable degree in absolute flux values and slope in the most important energy range, greater than 0.1 MeV, mainly because of uncertainties in the production and buildup of secondary nucleons in high-energy interactions. This buildup of neutrons determines not only the dose equivalent rate produced by galactic cosmic rays, but, as will be described later, it also determines about 50 percent of the dose equivalent in the case of the high-energy February 1956 event, apparently the only kind of solar event of significance for SST operations. The Monte Carlo calculations of Leimdorfer et al. (ref. 23) are applicable only to primary protons with energies up to 450 MeV, and for the case of the February 1956 event, they yield only lower limits of dose equivalents for SST altitudes. Treating all higher energy primaries as 450 MeV particles still leaves an uncertainty of a factor of 3 for the upper limit, as was found by comparison of measured galactic cosmic ray dose equivalents and galactic cosmic ray dose equivalents calculated in this way. (See ref. 24.) Thus, the estimates for the early phase of the February 1956 event still varied between 500 and 8000 mrem/hr, partly because of the uncertainties in calculating biologically important secondaries.

In general, the buildup of secondaries and especially of the biologically important energetic neutrons produced by primaries of energies greater than 450 MeV has been particularly uncertain in magnitude and spectral content, as well as in the corresponding dose equivalent rates.

To contribute to a solution of this question of biologically important components and dose equivalents at high altitudes and thus to assist in establishing a position on operational requirements for commercial SST operations, the NASA Langley Research Center and New York University have, since 1965, conducted measurements of the fast neutrons in the energy range of 1 to 10 MeV in the atmosphere, especially in high latitudes, with neutron spectrometers, using pulse-shape discrimination techniques, and of tissue-absorbed dose rate with tissue equivalent ionization chambers. These instruments were supplemented in some of the flights by large nuclear emulsion stacks to measure with satisfactory statistics the few heavy primaries and heavy fragments expected at SST altitudes. During the period 1965 to 1968, measurements were made up to altitudes of 42 km (137 000 ft) with up to six balloon flights per year, which were provided by the Skyhook Organization of the Office of Naval Research.

Airplane flights up to anticipated SST altitudes were conducted during 1966 and 1967 with the cooperative assistance of the Air Force Systems Command. Further airplane flights at SST altitudes have been conducted since 1968 with the assistance of the Air Force Chief of Operations, Air Force Weather Service, and Air Force Weapons Laboratory (AFWL) in conjunction with the FAA-AFWL High-Altitude Radiation Environment Study (HARES). The first measurements of fast neutrons produced by solar particles were obtained on November 18, 1968, February 29, 1969, and March 30, 1969, during low-intensity solar events and are reported separately.

In addition to the program of experimental measurements in solar cycle 20, and theoretical estimates of the upper and lower limits of dose equivalents produced by the intense and energetic solar cosmic ray events of cycle 19 (ref. 24) on the basis of Monte Carlo calculations for incident protons of energy <450 MeV, the NASA Langley Research Center began to collect data and assemble and develop computer programs for the transport of nucleons and mesons in the GeV range. The basic Monte Carlo transport code that was developed by Leimdorfer and Crawford (ref. 25) for energies less than 450 MeV was extended by John W. Wilson at Langley to the GeV range by using the recent high-energy cross-section data of Bertini (ref. 26), the data being reduced to a suitable format by R. G. Alsmiller of Oak Ridge National Laboratory. This code was used to compute the buildup of biologically important secondaries; the dose estimates for giant-energy events such as that of February 1956, as well as for low- and medium-energy events and for the galactic cosmic protons, could thence be considerably improved, in particular with respect to the biologically important and penetrating neutron component.

The principal purpose of the present paper is to present the dose equivalent rates from galactic cosmic rays as functions of altitude for various degrees of solar activity, as they are obtained from these measurements and theoretical calculations, taking into

account star measurements in tissue equivalent emulsions of British scientists,[2] which were made at about the time that the NASA program began. In addition, the improved estimates of dose equivalent rates at different altitudes produced by high-energy solar events like that of February 1956 and by other significant solar events of the highly active cycle 19 (1954 to 1964) obtained on the basis of the new Langley high-energy proton transport code, which is discussed in the appendix, are presented. As yet, only high-latitude doses are analyzed which establish the maximum values of exposure at SST or subsonic jet altitudes. The dose equivalents from solar and galactic cosmic rays obtained for crew and passengers are then compared with the maximum permissible doses established by the International Commission on Radiological Protection (ICRP) for radiation workers and for individuals of the general population.

Since on the basis of the results to be presented, the (relatively few) passengers encountering a rare giant-energy solar event such as that of February 23, 1956, could be overexposed at SST altitudes, radiation monitoring systems, effective safety measures, and implications concerning the design and operation of commercial SST craft are mentioned.

In section IX the most important scientific results of the Langley — NYU high altitude radiation study from 1965 to 1973 obtained so far, and a number of significant related unsolved problems are reviewed. The findings on atmospheric neutron spectra and on their variations with altitude, latitude, and solar activity led besides to the determination of dose equivalent rates at high altitudes, to a new determination of the time-dependent worldwide radiocarbon production rate within the atmosphere, and of the leakage rates out of the atmosphere. Related unsolved problems are the biological effects of low doses of neutrons and heavy primaries and the prediction of the contribution of α and heavier nuclei to the secondaries in air or other matter.

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[2]Work by P. J. N. Davison under M. O. A. Grant PD/34/017, Brit. R. A. E., 1967.

II. TERMINOLOGY, UNITS, AND CONVERSION FACTORS

The definitions of doses and units used in radiology are given in the recommendations (1968) of the International Commission on Radiological Units and Measure (ICRU) (ref. 27). A simplified definition of absorbed dose and of dose equivalent may be recalled here for convenience.

The biological effect of a quantity of "lightly" ionizing particles, that is, particles having low linear energy transfer (LET), is measured by the amount of energy absorbed per gram of tissue ("absorbed dose," D). The basic unit of absorbed dose is called the rad (1 rad = 100 ergs/g-tissue). It is a satisfactory measure for the effects of X-rays, primary electrons, mesons, and high-energy protons and alpha particles. Particles of higher LET (that is, more heavily ionizing along their paths) cause greater biological effects for the same absorbed dose (in rads). The most significant of the heavily ionizing particles are heavy nuclei and low-energy protons and alpha particles. (Low-energy protons are the main products of fast neutrons in tissue.) In current radiation protection practice, therefore, an indication of the effect upon a given organ is inferred by weighting the absorbed dose in that organ by an average quality factor Q_F which is defined as a function of the average linear energy transfer of the charged particles within the irradiated medium. The product of this radiation response modifying factor Q_F and the absorbed dose D is called dose equivalent (DE), the unit of which is the rem. Thus,

$$DE(rem) = Q_F \times D(rad)$$

The relation between average LET and Q_F is established empirically and conservatively by the ICRP for radiation-protection guideline purposes. (See ref. 28.) In these guidelines, the maximum permissible doses (MPD) are given in rem.

The first fluence-to-dose conversion factors for neutrons in the energy range between thermal energies and 10 MeV and for tissue slabs with thicknesses up to 30 cm ($\approx$12 in.) at normal incidence were calculated by the Monte Carlo method and published by Snyder and Neufeld in reference 29. The program first found the numbers and energies of charged primaries and secondaries in each volume of the tissue phantom and then determined for each particle the energy deposited per gram (rad) and the energy deposited per unit path length, the linear energy transfer (LET), which depends on both the particle and its energy. Finally, the dose equivalent (rem) is determined by multiplying the absorbed dose by the corresponding quality factor Q_F (a function of LET) and summing over all particles.

It turns out that the contribution of neutrons with energy up to 0.1 MeV is negligible for spectra encountered in the high atmosphere because of their small number and low-

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energy deposition per neutron. The relative intensities of neutrons in the 0.1 to 400 MeV energy ranges, which have high quality factors, turn out to be the main contributors to the neutron dose equivalent rate.

The conversion factors for protons and neutrons in the energy range 0.1 to 400 MeV for both isotropic and normal incidence and for various depths within a 30-cm-thick tissue slab (surface, 5-cm ($\approx$2 in.) depth, average and peak doses) are presented in references 30 to 33. In the following calculations the average doses in the slab are considered to be representative of the average body doses of occupants in an aircraft. The doses in the center of the human body are approximated by the doses in the center of a spherical tissue phantom (30-cm ($\approx$12 in.) diameter). For this center dose in the case of the neutrons that arrive about isotropically from the upper and lower half spheres, two times the average dose in the 30-cm ($\approx$12 in.) slab is taken. The factor 2 corrects for additional self-shielding in the slab and has been verified by measurement of the neutron flux inside and outside a spherical tissue phantom at high altitudes. The inside observed counting rates were, within a wide altitude range, in agreement with those calculated as described above from the incident neutron flux measured outside the phantom. These spherical rad and rem doses overestimate the doses in the center of the body trunk because the human body provides more shielding in the vertical direction.

The doses for the extremities (hands, feet) and, approximately, for the eyes are estimated in the present paper from the referenced flux to surface dose rate conversion factors for the 30-cm ($\approx$12 in.) slab, calculating, for example, the neutron doses from the isotropic fluxes incident from above and below as if the total flux came from one side.[3] (The contribution to the slab surface dose from secondaries produced in the depth of the slab and scattered back can be neglected.)

Shown in figure 1(a) are these skin dose conversion factors for neutrons. Irving et al. (ref. 32) using Dresner's evaporation code (ref. 34) found dose equivalent conversion factors for neutrons in the energy range 10 to 60 MeV which are considered to be too high. In this range the cited authors computed the conversion factors by using the compound nucleus model in which all of the incident neutron energy was released through evaporation particles, which is certainly not the case. This evaporation process without an initial intranuclear cascade (the intranuclear cascade was used by Bertini) causes a too high production of especially low-energy alpha particles which, because of their high quality factor, give a substantial contribution to the dose equivalent. (See table 4 of ref. 32.) This "anomalous" alpha particle contribution is shown as the upper bound of the

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[3]Below 60 MeV, the maximum dose and skin dose are the same (refs. 30 and 31). With increasing energy the position at which the maximum occurs slowly moves deeper into the tissue slab because of buildup of secondaries in tissue until at 300 MeV the maximum occurs on the backside. In the range of 60 to 400 MeV, the surface dose conversion factors of references 30 and 31 were considered to be satisfactory for thin members, like hands and feet.
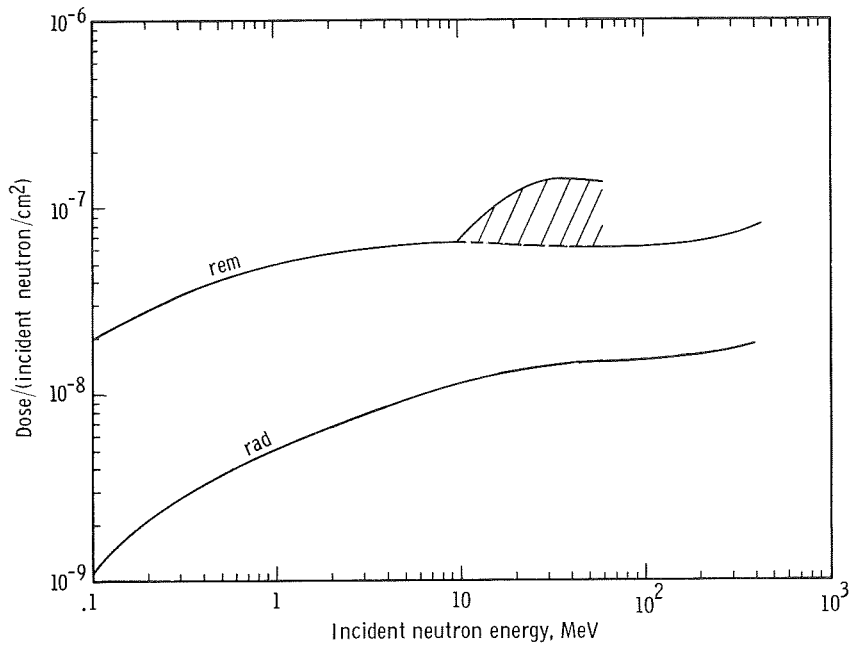
(a) Factors used in the calculation of neutron doses in extremities.
The hatched area of the rem curve is the uncertainty resulting
from using two different reaction models.

X Kinney and Zerby, refs. 30 and 31
• Turner et al., ref. 33
△ Armstrong and Chandler, ref. 35
○ Alsmiller et al., refs. 36 and 37
— Used in present calculation
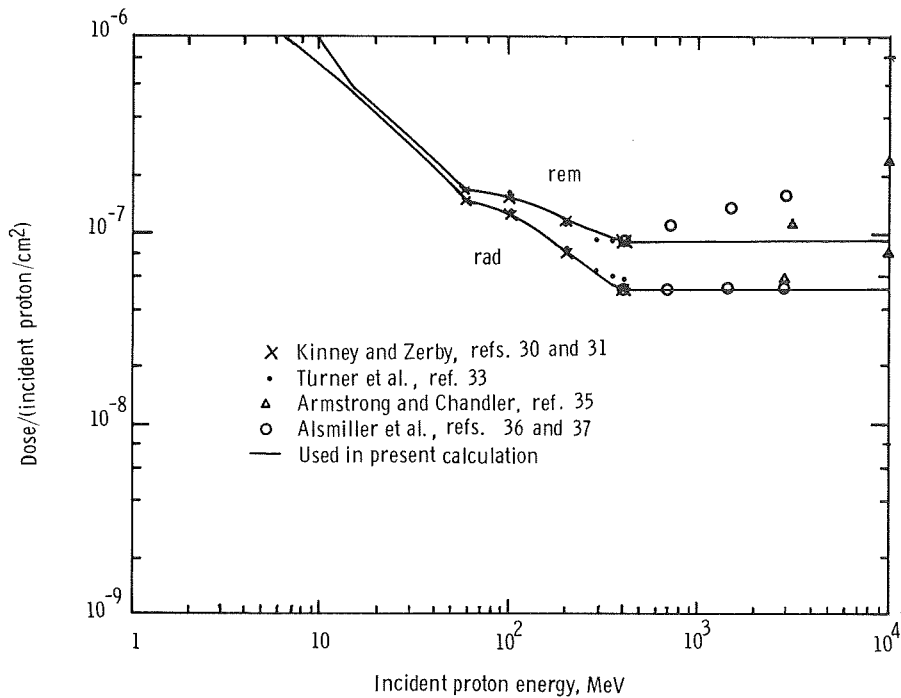
(b) Factors used in the calculation of proton doses in
small tissue sample (curve).

Figure 1.- Skin dose conversion factors for isotropic incident neutrons and protons.

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hatched area, whereas the lower bound is obtained by interpolation from 10 MeV to the results of Kinney and Zerby (refs. 30 and 31) at 60 MeV, which were calculated by using the intranuclear cascade and evaporation model of Bertini. The effects of this anomalous alpha contribution are also noted in the next section and in figure 6. Recent experimental data on the production of intermediate- and low-energy heavy nuclei in nuclear interactions indicate that the contribution to the dose equivalent is more than that predicted by the intranuclear cascade plus evaporation model (lower rem curve in fig. 1(a)) but less than the contribution predicted by the compound nucleus model (upper rem curve in fig. 1(a)). In this paper the compound nucleus model (the top curve of the hatched area) is used. The conversion factors for skin-absorbed dose (rad) shown in figure 1(a) were obtained by using the factors for maximum dose below 60 MeV of reference 32 and the skin dose factors from 60 to 400 MeV of references 30 and 31. There is no lump in the rad curve because the absorbed dose is approximately the same whether the energy is released as protons or as alphas.

The fluence-to-dose conversion factors for protons in the energy range 60 to 400 MeV were again taken from Kinney and Zerby (refs. 30 and 31); below 60 MeV nuclear reactions were neglected (ref. 33). Above 400 MeV it was assumed that the conversion factors are approximately energy independent; thus, the values at 400 MeV were used.

The proton fluence-to-dose conversion factors for skin and for extremities are shown in figure 1(b). Also shown for comparison are recently calculated dose conversion factors for proton energies >400 MeV (refs. 35 to 37). The dose equivalents per proton D show a steady increase for these higher incident energies, which may be roughly approximated as

$$D = D_{400}(0.96 + 10^{-4}E)$$

where D_{400} is the value at 400 MeV. The largest error in using the 400 MeV value over this entire high-energy range would be incurred for the most energetic spectrum at the top of the atmosphere. The calculation shows that the total dose equivalent error would be less than 10 percent for even the galactic cosmic rays.

III. DESCRIPTION OF FLIGHT INSTRUMENTATION, SAMPLE EXPERIMENTAL RESULTS FOR GALACTIC COSMIC RAYS, THEORETICAL EXTRAPOLATION OF THE NEUTRON SPECTRA, AND CALCULATION OF NEUTRON DOSE RATES

The complement of instruments used to measure neutron spectra, tissue absorbed dose rate, and heavy primaries in the NASA Langley-New York University program are as follows:
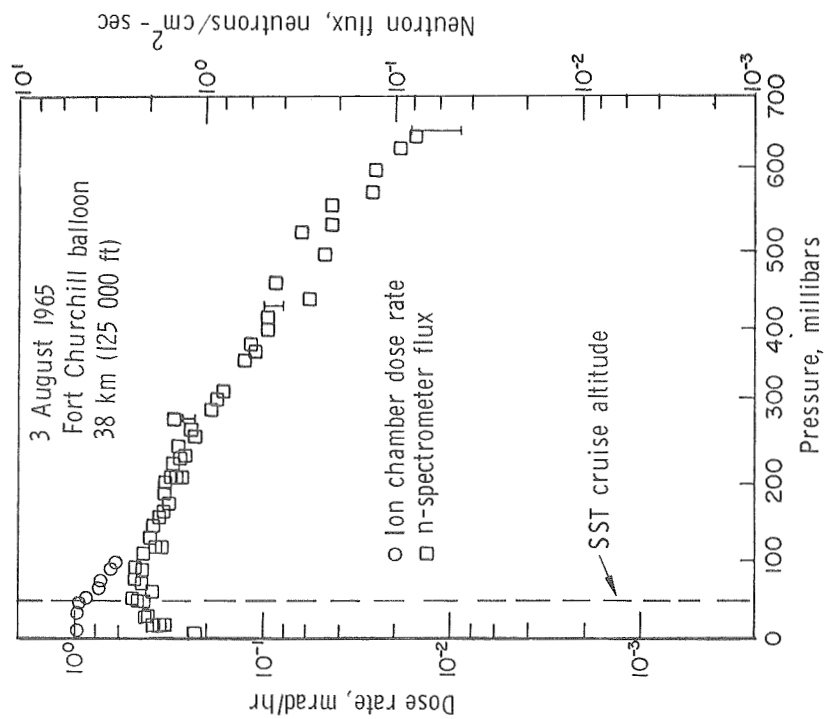
Figure 2.- Galactic cosmic ray maximum (August 1965, 1 year after sunspot minimum, Fort Churchill, geomagnetic latitude ≈69°). Neutron fluxes in the range 1 to 10 MeV (right scale) and ion chamber dose rates (left scale) as a function of altitude.
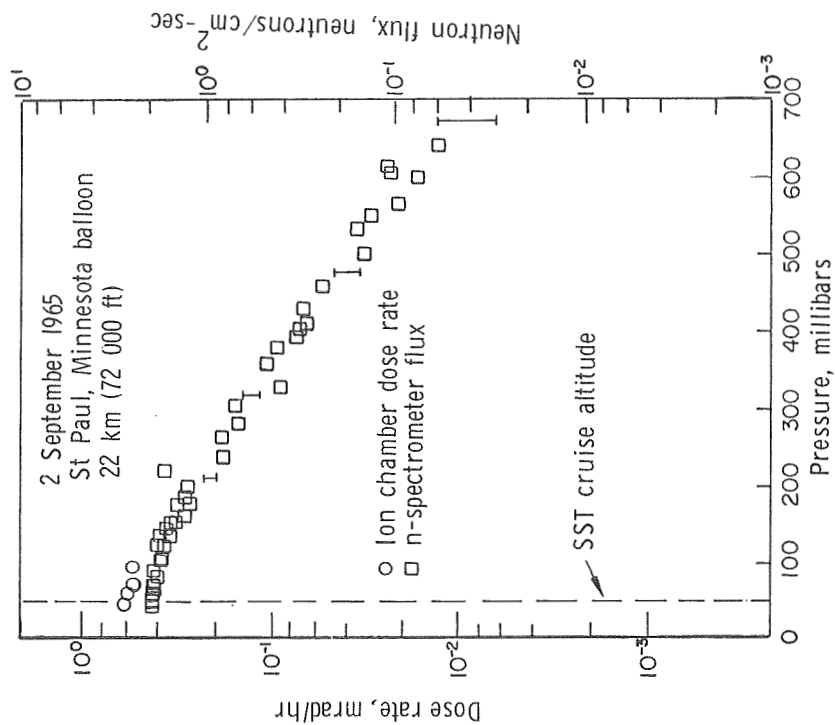
Figure 3.- Galactic cosmic ray maximum (September 1965, Minnesota, geomagnetic latitude ≈55°). Neutron fluxes in the range 1 to 10 MeV (right scale) and ion chamber dose rates (left scale) as a function of altitude. Compare with figure 2 data at higher latitude.

(a) Phoswich neutron scintillator NE-218 spectrometer designed by R. B. Mendell and S. A. Korff (ref. 38) which measures the recoil proton fluxes in seven energy channels in the range 1 to 10 MeV. The neutron scintillator is encapsulated with an NE-102 scintillator for charged particle rejection. Pulse-shape discrimination is used to reject counts from gammas and charged particles. The neutron differential energy flux is found by assuming the energy spectrum to be of the form AE^{-X}, and determining A and x so as to be most consistent with the recoil proton spectrum (recorded in the seven channels) in a least-squares sense.

(b) Tissue equivalent ionization chamber, designed and built by Avco in Tulsa, Oklahoma, according to the specifications of M. F. Schneider, AFWL (ref. 39), the recorder section being designed by Richard R. Adams of NASA Langley, who also supervised the calibration, testing, maintenance, and data reduction.

(c) Large nuclear emulsion stacks, large enough to obtain satisfactory statistics on the few heavy primaries and energetic heavy secondaries at SST altitudes.

Data from several balloon flights are presented in figures 2 to 5. The absorbed doses measured in the ion chamber (circles) are read according to the scale at the left, whereas neutron fluxes (squares) are read according to the scale at the right. These data were chosen to demonstrate the general effects of latitude, altitude, and solar cycle variations on the galactic cosmic ray produced radiation fields (both in the air and in a tissue phantom). The neutron flux error bars are determined from the statistical variation of the count samples (one sample per minute). The ion chamber data for atmospheric depths greater than 150 g/cm² are not shown because of the delayed response of the ion chamber during ascent due to the low ionization rate. This delayed response is measured by control pulses during ascent and descent and is taken into account in the final evaluation in figures 7 and 8 in the next section.

Figure 2 shows the measurements made on a high-altitude balloon flight during galactic cosmic ray maximum at 69⁰ geomagnetic latitude. The instruments for this flight were only lightly shielded (less than 1 g/cm² of fiber glass and foam for thermal insulation). The features to be noted in figure 2 are the broad maximum in the neutron flux, with peak at 60 to 70 millibars and the leveling off of the ion chamber dose rate above 50 millibars (1 mb $\approx$ 1 g/cm²).

Figure 3 shows data from a low-altitude balloon flight during galactic cosmic ray maximum (1 month after the flight shown in fig. 2) at 55⁰ geomagnetic latitude. Note that although the ionization dose rate is considerably reduced, the neutron flux has changed less. These reductions are due to the increase in geomagnetic cutoff energies in going to lower latitudes. The proton cutoff at Fort Churchill (geomagnetic cutoff, 2 MeV) caused by solar modulation may have been in the order of a few hundred MeV, and the geomagnetic
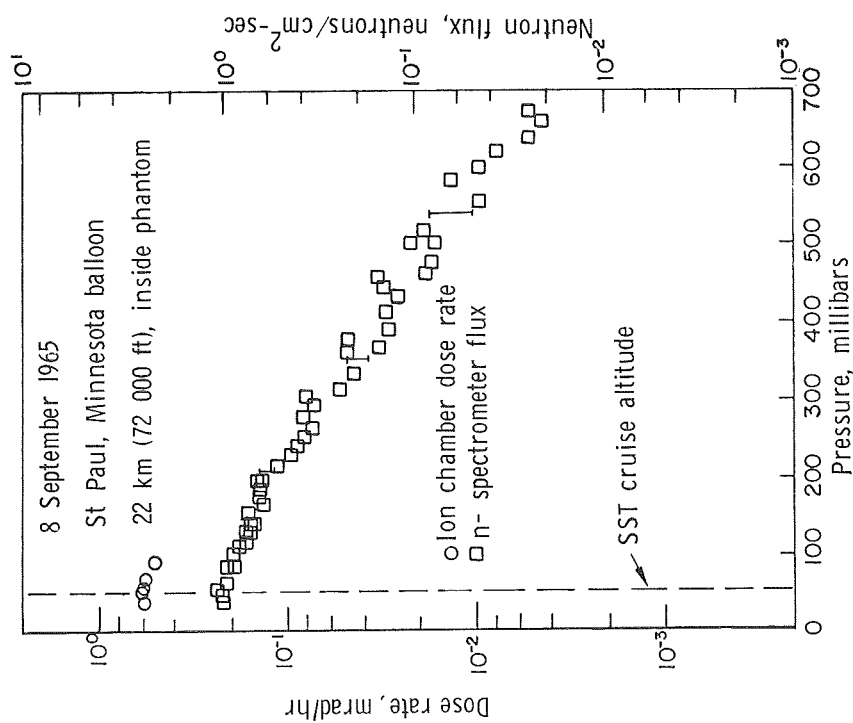
Figure 4.- Galactic cosmic ray maximum (September 1965, Minnesota, geomagnetic latitude ≈55°). In the flights of figures 2 and 3, the sensors were lightly shielded (less than 1 g/cm2 of fiber glass and foam). In this flight, the sensors were surrounded by tissue equivalent material, including calcium, of about 15 g/cm2 thickness, to measure approximately the neutron fluxes and ion chamber dose rates in the center of the human body.
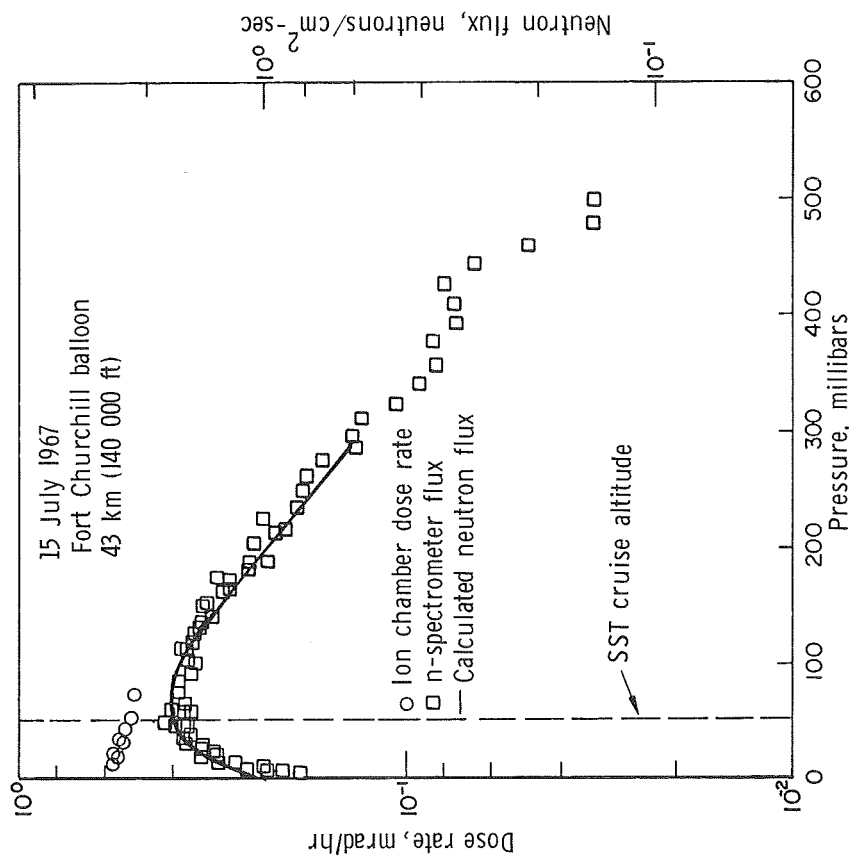
Figure 5.- Galactic cosmic rays 2 years after galactic cosmic ray maximum (July 1967, Fort Churchill, geomagnetic latitude ≈690). Compare with figure 2 for a flight at galactic cosmic ray maximum. The neutron flux and ion chamber dose rate have both decreased about 25 to 30 percent at SST altitudes (solar modulation). The solid line is the altitude dependence obtained by theory (see appendix).

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proton cutoff at St. Paul during the magnetically quiet period at the beginning of September 1965 was ≈800 MeV.

Shown in figure 4 are data from a second flight above Minnesota. This flight differs from the one shown in figure 3 in that the ion chamber and neutron spectrometer were placed in a spherical shell of tissue equivalent material (phantom) 15 cm or 15 g/cm^2 thick. The ion chamber dose rate is not appreciably changed from the earlier flight. (See fig. 3.) The neutron flux has decreased significantly; and the neutron energy spectrum was found to be flatter in the 1 to 10 MeV range. This reduction is due to the relatively large moderation of neutrons of energies below about 10 MeV by the hydrogen in the phantom, which outweighs the production of new neutrons by the calcium, carbon, and nitrogen in the phantom.

In figure 5 are plotted data from a flight from Fort Churchill in a period of increased solar activity, which is typical for about 2 years after galactic cosmic ray maximum. The ion chamber dose rate and the neutron flux decreased by about the same percentage during the 2 years. These decreases are due to a corresponding increase of the scattering power of the interplanetary magnetic fields. The solid line in figure 5 is the shape of the altitude profile of neutron intensities 1 to 10 MeV as obtained from the theoretical nucleon cascade calculations described in the appendix.

Table I contains neutron fluxes and spectral indices in the range of 1 to 10 MeV for flights during 1965 to 1968 in high latitudes at approximately 60 g/cm^2 atmospheric depth or an altitude of 20 km (65 000 ft).

TABLE I.- NEUTRON FLUX (INTEGRAL FLUX IN THE RANGE 1 TO 10 MeV)

AND SPECTRAL INDEX (DIFFERENTIAL ENERGY SPECTRUM ≈AE^{-x})

AT SST ALTITUDE

Date	Location	Shielding	Flux, neutrons/cm2-sec	Spectral index, x
Aug. 3, 1965[*]	Ft. Churchill, Canada	Air	2.46	1.26
Sept. 2, 1965	St. Paul, Minnesota	Air	2.16	1.29
July 15, 1967[*]	Ft. Churchill, Canada	Air	1.81	1.23
July 18, 1968[*]	Ft. Churchill, Canada	Air	1.52	1.16
Aug. 9, 1965[*]	Ft. Churchill, Canada	Air + phantom	1.35	.96
Sept. 8, 1965	St. Paul, Minnesota	Air + phantom	1.08	.86

[*]Used in dose calculations.

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These data were supplemented by theoretical extrapolations of the neutron spectra (see refs. 40 to 45 and the appendix) in the range 0.1 to 1 MeV according to the spectral shape calculated by Newkirk (ref. 21) and in the range 10 to 500 MeV according to the flat spectral slope ($E^{-1.2}$), first found by John W. Wilson by Monte Carlo nucleon transport calculations on the basis of neutron production cross sections for incident protons up to 2 GeV energy of Bertini (ref. 26) and semiempirical extrapolation to 10 GeV.[4]

In figure 6, as an example for the neutron dose determinations, the neutron spectrum from galactic cosmic rays measured in the range 1 to 10 MeV at SST altitude on August 3, 1965, above Fort Churchill is extrapolated by the preceding method to lower energies (0.01 MeV) and higher energies (500 MeV); the results of the Monte Carlo calculations are shown by the horizontal dashes, representing the neutron fluxes compiled in the corresponding energy bins. From this spectrum the rad and rem rates for hands and feet due to neutrons are obtained by summing the dose rates resulting from multiplying the flux in each energy interval by the corresponding flux-to-dose rate conversion factor for the extremities. (See the previous section.) The resulting rad rate is 0.123 mrad/hr and the corresponding rem rate is 0.863 (0.772) mrem/hr; the two values without and within parentheses are considered upper and lower limits. (See discussion of flux-to-dose conversion factors and "anomalous" α contribution in the previous section.) In addition to the spectrum, the separate contributions in the different energy ranges to the rad and rem rates are indicated in figure 6 (linear scale on right-hand side).[5] The difference between the rem and rad rate areas is the damage increment of neutrons used in the next section. The neutrons of energies greater than 10 MeV are found to contribute (through recoil protons and stars) 35 percent to 43 percent to the total dose equivalent rate of neutrons. The neutrons of energy 0.1 to 1 MeV, assumed to have an energy spectrum similar to that given by Newkirk, contribute about 27 percent. The unmeasured part of the spectrum thus contributes about 70 percent to the neutron dose equivalent rate in extremities.[6]

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[4]A similar nucleon transport code for incident protons up to 450 MeV energy was previously developed by the Neutron Division of Oak Ridge National Laboratory (refs. 46 and 47); however, at that time (1968), it was not extended to incident protons in the GeV range.

[5]This figure was contained in a more detailed version of reference 40 distributed in 1969 to FAA Advisory Committee for Radiobiology Aspects of SST, to Neutron Division of Oak Ridge National Laboratory, and to New York University.

[6]The dose rates throughout this paper are for the unshielded body or tissue slab and do not take into account secondaries (especially neutrons) produced in the airplane masses surrounding the passengers or crew. Comparison of neutron spectra and tissue doses measured under balloons with those measured in high-altitude airplanes (B-57F) does not indicate that the airplane masses increase the neutron spectra and dose rates by more than 5 to 10 percent, which is within the error limits of the measurements.

Galactic C.R. maximum (3 August 1965) altitude = 70000 ft (21 km)
≈ 50 g/cm²

Extremities
neutron dose equivalent rates: Total NASA = .772 to .863 m-rem/hr ⎱ ratio
                                  Total ICRP-T.G.(Ref. 13)= .168 m-rem/hr ⎰ 4.6-5.1
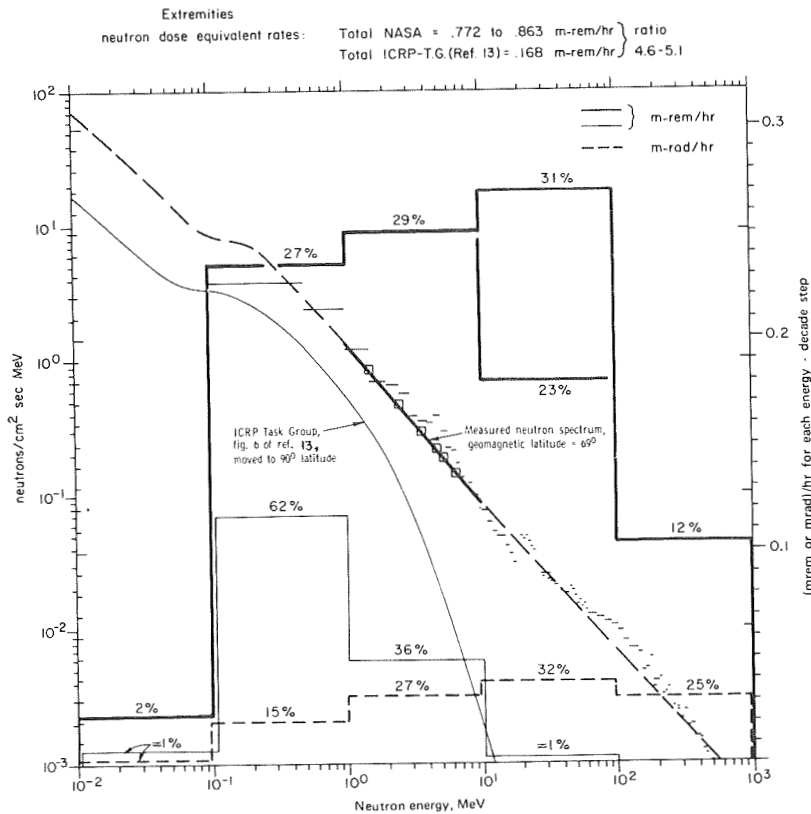
Figure 6.- The high-latitude (geomagnetic latitude ≈ 69°) neutron spectrum measured at SST altitudes (≈50 g/cm²) on August 3, 1965 (heavy solid line between 1 and 10 MeV) by Mendell, with its extension to lower and higher energies (heavy dashed curve) compared with the shape of the Monte Carlo spectrum (histogram, horizontal dashes). Also shown is the neutron spectrum (light solid curve) used by the ICRP task group (ref. 13, fig. 6, 41° geomagnetic latitude, adjusted to 90° latitude). The right-hand linear scale is for the dose rates in extremities calculated from the NASA spectrum (rem — heavy step curve; and rad — dashed step curve) and for the rem rates (light step curve) as taken from the ICRP task group report. The difference between the two 10 to 100 MeV steps on the heavy step curve is the "anomalous" α-particle contribution.

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For comparison, the neutron spectrum and the rem and rad rates for neutrons, as taken from the ICRP task group report (tables 1 and 5 and fig. 6 of ref. 13; the spectrum at 50 g/cm^2 is adjusted from 41$^\text{o}$ latitude to 90$^\text{o}$ latitude by multiplying by 2.6, according to table 1 of ref. 13), are plotted in light lines. Comparison of the areas under the corresponding step curves shows that the dose equivalent rate for neutrons derived by NASA from measurements and calculations is higher by a factor of about 5 than that given in the ICRP task group report. This factor of about 5 is due to the higher flux values measured in the energy range below 10 MeV and the much flatter slope of the spectrum in the energy range 10 to 500 MeV found by the Monte Carlo calculations.

The main results of these measurements on galactic cosmic rays are the determinations of the absolute values of the energetic secondary neutron fluxes (1 to 10 MeV) and of their flat spectrum, which were in doubt before the present experiments, especially for high latitudes and altitudes, and the measurements with tissue equivalent ion chambers, which also yielded the contribution of neutrons (via recoil protons) to the absorbed dose (rad) in tissue, which is not obtained in conventional metal-walled ion chambers. In addition, the actual measurements of neutron spectra and tissue dose rates inside a spherical body phantom experimentally relate the dose equivalents in thin tissue equivalent samples (corresponding to the extremities) to the depth dose equivalents in the human body, and thus confirm theoretical calculations.

The theoretical spectra have as yet to be normalized by adjusting the absolute intensities to the measured neutron spectra in the 1 to 10 MeV range. The theoretical spectra are based on calculations for proton primaries and do not accurately take into account the α-particles and heavier nuclei that are present in galactic and solar cosmic rays, because the secondary production cross sections in reactions with air have not been satisfactorily determined either theoretically or experimentally. For the present purposes, it is considered satisfactory to assume that only the intensity and not the shape of the neutron spectra at subsonic and supersonic jet altitudes is substantially changed by the heavier primaries. (See also section IX and the appendix of this paper.)

IV. GALACTIC COSMIC RAY DOSE EQUIVALENT RATES AT HIGH LATITUDES AS A FUNCTION OF ALTITUDE FOR DIFFERENT PHASES OF SOLAR CYCLE; DOSE RATES FOR CREW AVERAGED OVER SOLAR CYCLE

Galactic Cosmic Ray Dose Equivalent Rates in Extremities (Hands, Feet, . . .)
and Inside a Spherical Body Phantom, Measured and Calculated

The various contributions to the total dose equivalent rate as measured in high latitudes for the initial phases of the present solar cycle (1965 to 1968) are shown in figures 7 and 8. The different contributions in the figures correspond to the types of instrumenta-

tion with which the measurements were made. The tissue equivalent ion chamber measures only the energy deposited in a thin tissue sample (that is, absorbed dose rate in mrad/hr) by all radiation components. This measurement, however, does not provide the biologically equivalent dose rate since much of the dose equivalent rate (mrem/hr) is due to components with a quality factor Q_F greater than unity, such as proton recoils and heavily ionizing star prongs in tissue from neutron and charged-particle reactions with tissue nuclei. These contributions to the excess of the total dose equivalent over the corresponding absorbed dose given by the tissue equivalent ion chamber (mrem minus mrad) are referred to as the damage increments. They are derived by analysis of the neutron spectrometer and tissue equivalent nuclear emulsion data. (The nuclear emulsion data from British R.A.E. were used, as explained subsequently.) The components of the total dose equivalent rate, derived from measurements and shown in figures 7 and 8, are thus:

(a) Tissue-absorbed-dose rate in mrad/hr from all radiation components, that is, from charged primaries and secondaries, including mesons, gamma rays, neutrons (via recoil protons, heavy recoils, and neutron-produced stars), and stars produced by energetic charged particles, all of which are measured in the tissue equivalent ion chamber. As explained before, some of these components have, because of their large linear energy transfer, a quality factor greater than unity. This excess constitutes parts (b) and (c).

(b) The damage increment rate (mrem/hr minus mrad/hr) produced in tissue by energetic neutrons (0.1 to 500 MeV) via recoils and stars.

(c) The damage increment rate (mrem/hr minus mrad/hr) caused by stars in tissue produced by primary and secondary charged particles.

Component (b), the neutron-damage increment rate, is found from the measured neutron fluxes in the range of 1 to 10 MeV extended to lower and higher energies as explained in section III (see fig. 6) by subtraction (rem rate minus rad rate). The neutron-damage increment rate on August 3, 1965, in SST altitude is thus found, for example, for the extremities as 0.74 mrem/hr (0.863 - 0.123, see p. 16 and fig. 6).

Component (c), the damage increment rate due to stars produced by charged particles, was derived from measurements at different altitudes in tissue equivalent emulsions by P. J. N. Davison, where the increment is referred to as "star damage energy." The total star damage increment derived by Davison included the contribution of neutron-produced stars which is already taken into account in (b); the star contribution from charged particles is approximately one-half of the total star damage increment at high altitudes (20 km (65 000 ft) to 34 km (110 000 ft)) and one-third the total star damage increment at subsonic altitudes (11 km (37 000 ft)), as theoretical calculations indicate. This part is plotted in figures 7 and 8. The total dose equivalent rate is obtained by summing parts (a), (b), and (c).
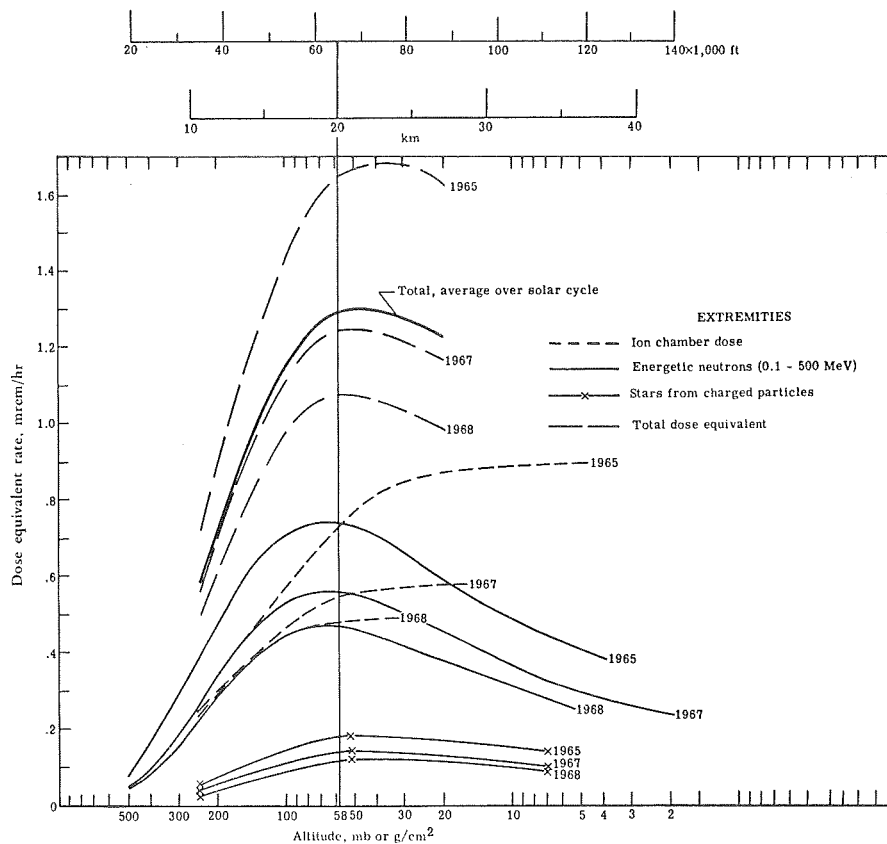
Figure 7.- Galactic cosmic ray dose equivalent rates for extremities
(hands, feet) and approximately for eyes as a function of altitude at
different phases of the solar cycle for high latitudes.

The total extremity dose equivalent rate in figure 7 in high latitudes as a function of
altitude exhibits a maximum at about 35 g/cm^2 (22 km or 75 000 ft) during galactic cosmic
ray maximum (approximately 1 year after sunspot minimum). The maximum decreases
in magnitude and appears to move deeper into the atmosphere as galactic cosmic ray min-
imum is approached. This peak is mainly due to the broad maximum in the neutron fluxes
at these altitudes. (See neutron data in figs. 2 and 5 and neutron contribution in fig. 7.)
The absorbed energy measured in the ion chamber does not exhibit this peak. It may fur-
thermore be noted that the neutron dose equivalent rate contributes about 50 percent to the
total dose equivalent rate at these altitudes.

An upper limit for the average dose equivalent rate over the solar cycle 20 is
obtained by multiplying the rates for 1965, 1967, and 1968 by 3, 4, and 4 years, respec-
tively, and dividing by 11 years. At 20 km (65 000 ft) an average extremity dose equiva-
lent rate of 1.3 mrem/hr is obtained and is considered to be representative for hands,
feet, and eyes. The value is weighted in favor of the early and final phases of the solar
cycle to be representative also for cycles with less activity or modulation.
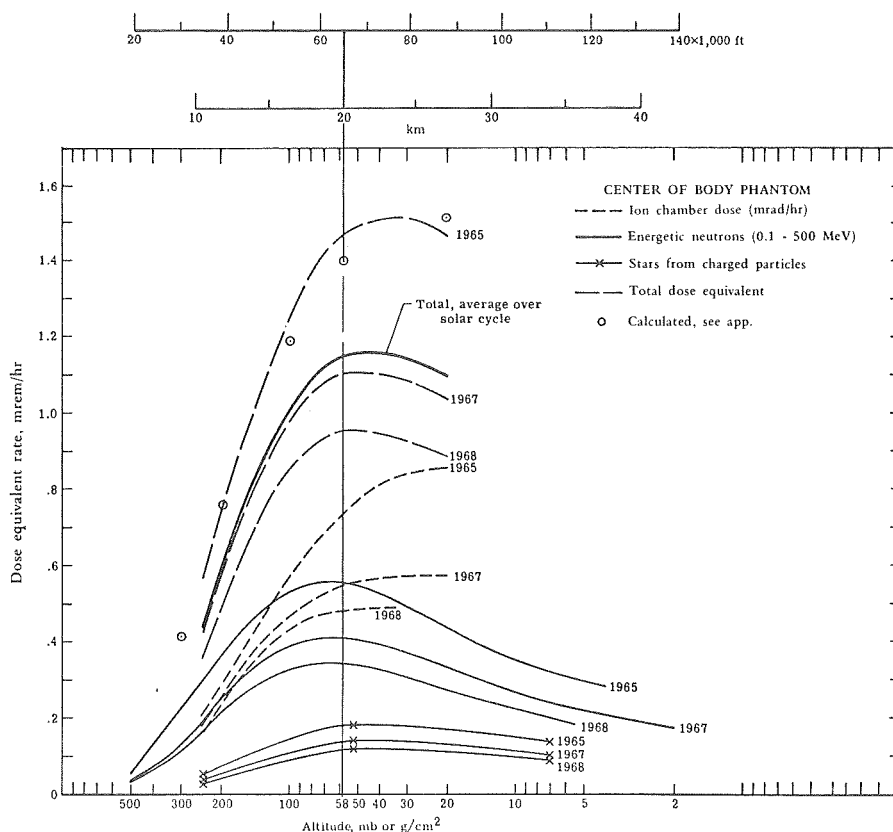
Figure 8.- Galactic cosmic ray dose equivalent rates for center of the human body as a function of altitude at different phases of the solar cycle for high latitudes.

In figure 8 is shown the dose equivalent rate in the center of a spherical body phantom (a spherical shell of 15 g/cm^2 wall thickness of tissue equivalent material) at high latitudes as a function of altitude. The three components were determined as follows: The ion chamber dose, component (a), was found with the ion chamber in the spherical phantom. The dose rates found with an ion chamber inside the phantom and with an ion chamber outside the phantom were found to be approximately the same in the same flight. (Compare also figs. 3 and 4.) Component (b) is derived from the neutron flux in the range 1 to 10 MeV, which was similarly measured inside and outside a sphere of 15 g/cm^2 wall thickness. The spectrum of neutrons was found to be significantly flatter within the phantom than outside the phantom. For example, a flight from Fort Churchill on August 8, 1965, with the neutron spectrometer inside the phantom, measured a spectrum in the range 1 to 10 MeV of $0.56E^{-0.96}$ neutron/cm^2-sec-MeV whereas a flight without the phantom on August 3, 1965, yielded the neutron spectrum $1.4E^{-1.26}$ neutrons/cm^2-sec-MeV in the range 1 to 10 MeV. The flattening of the spectrum as well as the reduction of the total flux is due to the moderating effect of the hydrogen-containing phantom, as noted in the previous section. The neutron spectrum (1 to 10 MeV) measured inside the spherical

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phantom on August 8, 1965, was extended from 1 to 0.1 MeV and from 10 to 25 MeV with the flatter spectrum and from approximately 25 to 500 MeV with $BE^{-1.2}$ where B is determined to provide continuity at $E = 10$ MeV with the measurements without the phantom as follows: $1.4 \times E^{-1.26} = BE^{-1.2}$ for $E = 10$, whence $B = 1.22$. The inside spectrum $(0.56E^{-0.96})$ intersects this outer spectrum at 25.6 MeV. By extrapolating the inside spectrum in this way, the assumption is made that high-energy neutrons $(E > 25$ MeV) were not moderated significantly by the phantom. The total dose rates (rad and rem) from neutrons were computed by using the flux inside the phantom as constructed above from the measured data and using the conversion factors for small tissue samples. For the center of the phantom at SST altitude, a value of 0.658 mrem/hr was obtained. This result has been compared with the neutron rem rate calculated for the center of the phantom from the measured neutron spectrum outside the spherical phantom. (See section II.) This calculated value is 0.630 mrem/hr which is in satisfactory agreement with the previously determined value of 0.658 mrem/hr derived from the inside spectrum.

The star damage increment from charged particles, component (c), was assumed not to be different inside the spherical phantom since these stars result from high-energy charged particles, which are not greatly affected by the 15 g/cm^2 spherical thickness (similar to the ion chamber dose rate). The average over the entire solar cycle of the center-of-body dose equivalent rate was calculated in the same manner as for figure 7.

These absolute values of dose equivalent rates for August 1965 as obtained from ion chamber, neutron, and star measurements at different altitudes are compared in figure 8 with the dose rates theoretically obtained by starting with the cosmic ray proton energy spectrum incident on top of the atmosphere and calculating the primary and secondary nucleon fluxes at high altitudes with the Langley nucleon transport code. The resulting neutron environment, presented in figure 6, is in agreement with the measured spectrum in the range 1 to 10 MeV. As was shown, application of the neutron dose rate conversion factors for the tissue sphere led to the same neutron dose equivalent rates inside the sphere as those derived from the measurements.

Insofar as protons are concerned, it turns out from the Monte Carlo calculations that the primary and secondary protons in SST altitudes and below have energies above several hundred MeV. As previously noted, for such energetic protons the dose rates in tissue including the contribution of the proton-produced stars are calculated to be the same for small samples and throughout a 15-cm-diameter tissue sphere. Therefore, for the sphere the dose conversion factors of figure 1(b) were used. The total dose equivalent rate for the center of the body trunk obtained by adding these calculated contributions of neutrons and of protons is plotted in figure 8 as circles.

The degree of quantitative agreement of the theoretically calculated dose equivalent rates (circles in fig. 8) and the dose equivalent rates derived from the measurements

(solid line) seems almost unexplainable, since no heavy galactic primaries are taken into account in the cascade calculations. The heavy galactic primaries should contribute to the secondaries at SST altitudes. On the other hand, the primary proton spectrum used in these calculations (see fig. 10 which was taken from ref. 48) is assumed to be the demodulated spectrum in local interstellar space without solar modulation. It does not take into account that the galactic cosmic ray intensity near the Earth is reduced in the range 0.1 to 10 GeV even at solar minimum, because of modulation by interplanetary magnetic fields. (See ref. 49.) Thus, use of the conservative values for the galactic proton spectrum will partly compensate for neglecting the contribution of heavy primaries. As noted before, because of the uncertainties caused by the lack of data concerning secondary production by the heavier particles, especially in α-air collisions, normalization of the theoretical secondary neutron spectra by measurements appears mandatory in order to approximate closely the real dose rate values.

Internal Dose Equivalent Rate of SST Crew Due to Galactic Cosmic Rays Averaged Over Solar Cycle

In figure 9, the average (over the solar cycle) dose equivalent rates for the extremities and for the center of the body are compared. It may be noted that self-shielding of the (spherical) body reduces the dose equivalent at the body center by only about 12 percent at SST altitudes. This self-shielding is due mainly to the moderation of neutrons.

From figure 8 the average internal dose equivalent rate of the SST crew due to galactic cosmic rays only, 40 hours/month or 480 hours/yr being assumed at cruising altitude at high latitudes, would be close to

$$1.2 \, \frac{mrem}{hr} \times 480 \, \frac{hour}{yr} \approx 600 \, \frac{mrem}{yr} \, \text{(galactic cosmic rays)}$$

which is roughly 12 percent of the average permissible dose rate for radiation workers (5 rem/yr) or 1.2 times the maximum permissible yearly dose for all individuals of the general population (0.5 rem/yr).

The exposure of passengers to galactic cosmic rays, negligible for most passengers because of their much lower frequency of travel, is discussed together with the solar cosmic ray exposure in later sections.
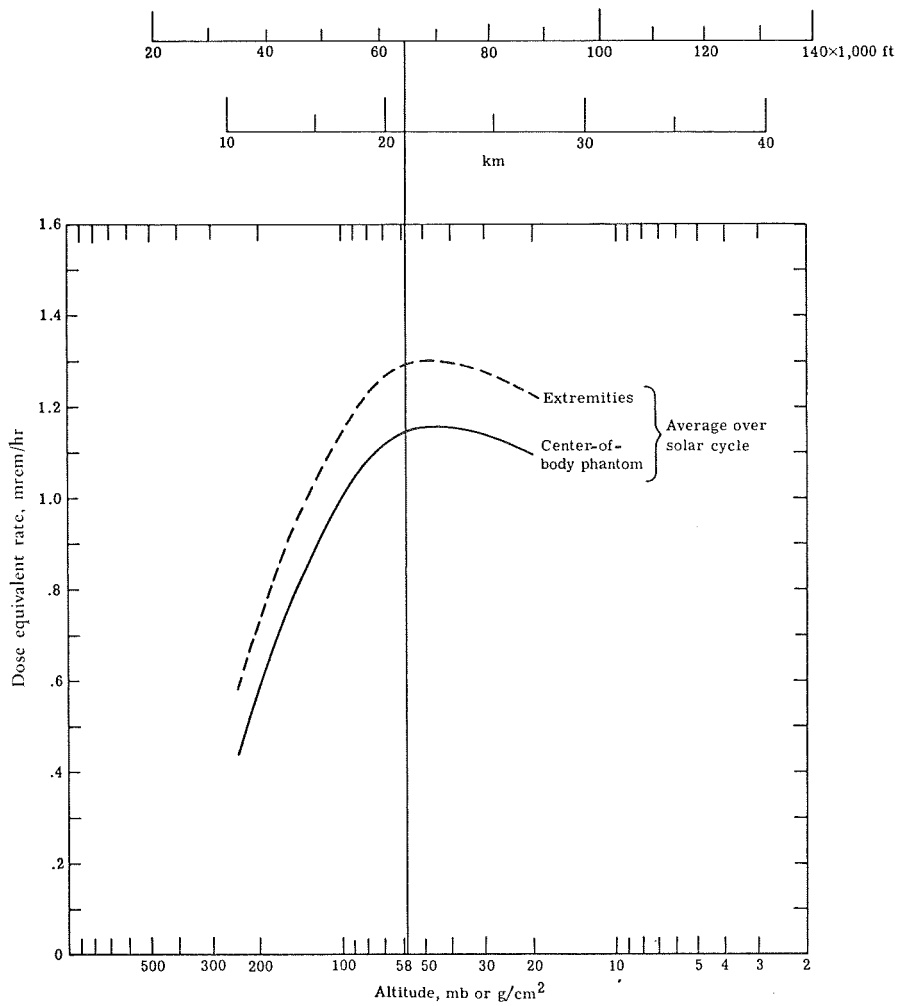
Figure 9.- Comparison of extremity and center-of-body galactic cosmic ray dose equivalent rates averaged over the solar cycle.

V. SOLAR COSMIC RAY DOSE EQUIVALENT RATES AS A FUNCTION

OF ALTITUDE IN HIGH LATITUDES

Dose Equivalent Rates in a Tissue Slab of 30-cm Thickness During

the Events of February 23, 1956, and November 12, 1960,

and Comparison With Previous Estimates

Figure 10 shows energy spectra above the atmosphere that are characteristic of giant-energy, medium-energy, and low-energy events of high intensity. (See ref. 12 and references cited therein.) The data on the prompt proton spectrum of the February 1956
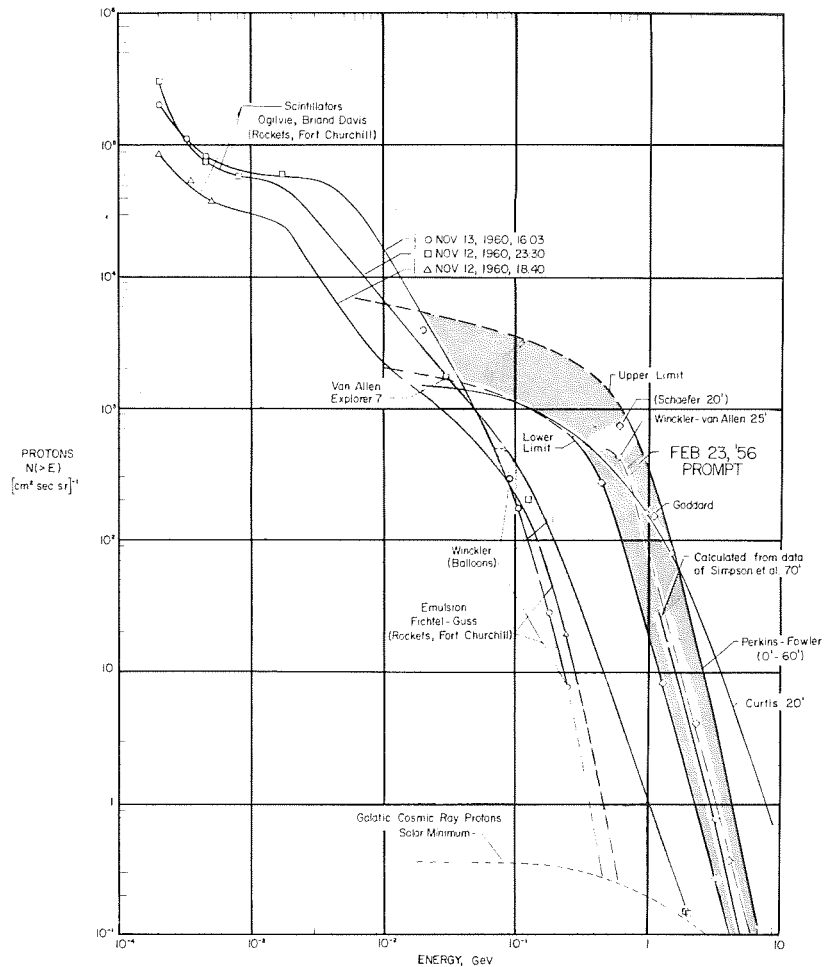
Figure 10.- Integral-flux energy spectra of extreme solar events. The prompt spectra of February 1956 were observed at different locations during the maximum phase of the event in the first hours after onset (composed from data cited in ref. 12). The spectra of the November 12-13, 1960, event were observed 5 (1840 UT), 10 (2330 UT), and 27 (1603 UT) hours after onset (composed from data cited in ref. 12). E is the energy of the protons in GeV and N is the number of protons in $(cm^2-sec-sr)^{-1}$.
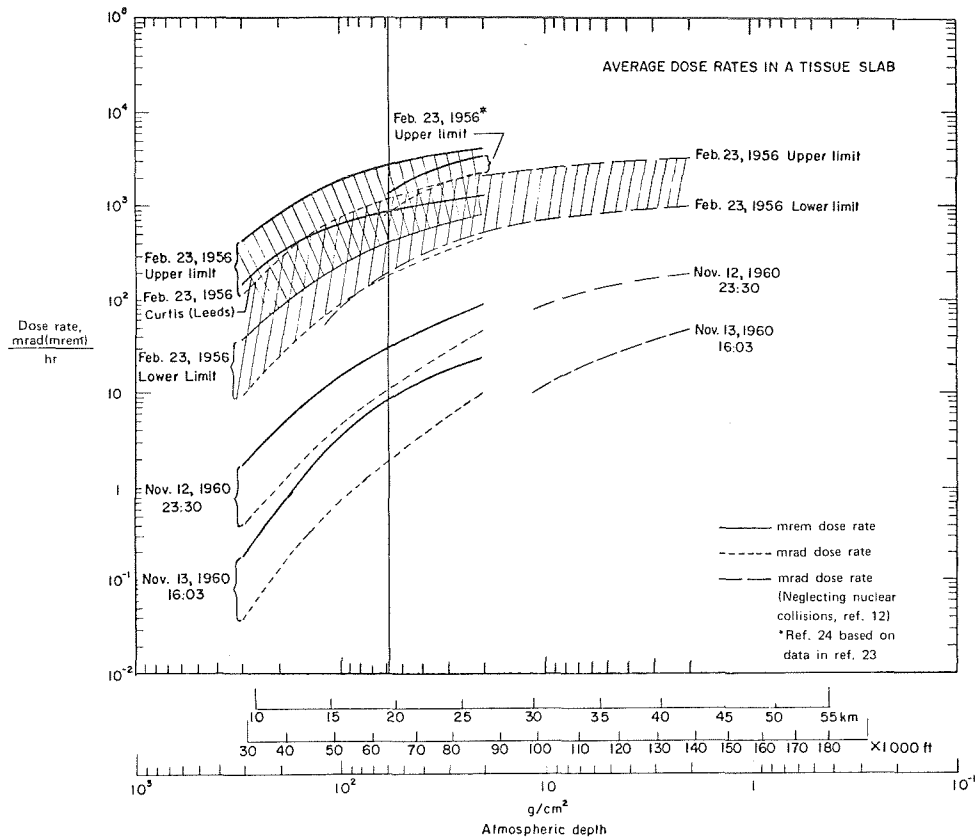
Figure 11.- Calculated average dose rates in a 30-cm-thick tissue slab during the large solar events of February 23, 1956 (maximum phase), and November 12, 1960, at 2330, and 1603 (November 13) UT, as a function of altitude.

giant-energy event are derived from sea-level neutron monitors at different latitudes on the ground $\left(\lambda_{magn} \gtrless 55^o\right)$. The fluxes are uncertain, especially in the energy range below 1 GeV, because the particles of lower rigidity are cut off by the magnetic field of the Earth in latitudes $\lessgtr 55^o$. The two spectra designated "upper limit" and "lower limit" bracket the estimates of most authors for the peak spectrum.

From the proton spectra above the atmosphere for February 23, 1956, and November 12, 1960, the dose rates as function of altitude were calculated with the Langley Monte Carlo code,[7] assuming that all incident particles were protons. The results are shown in figure 11 (left-hand side). For the February 1956 event, the rem and rad dose

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[7]In figure 11 the average dose rates in a 30-cm-thick ($\approx$12 in.) tissue slab are presented. The skin or eye dose equivalent rate without protection by the airplane could have been higher by a factor of about 2.5. During the preparation of this paper, which was presented in an abbreviated form at the FAUSST VII Meeting, Paris, France, March 3, 1969 (ref. 40), a paper by T. W. Armstrong et al. appeared (ref. 50) in which the dose rates for the upper and lower limit spectra of February 1956 are independently calculated. The dose rates calculated in reference 50 appear to be an upper bound to the extremity dose rates. (The skin dose rates for protons and maximum dose rates for neutrons throughout a 30-cm ($\approx$12 in.) slab of tissue are calculated and added together.)

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rates are shown as broad strips, the upper and lower limits differing by a factor of about 6, because of the large uncertainties of the prompt particle spectrum.

For November 12, 1960, the primary spectra are considerably better known since they were measured in satellites and were also measured with emulsions in rockets. The dose rates are therefore shown as lines. It may be noted in figure 11 that the neutrons carry the dose equivalent rate to considerably greater atmospheric depth than could be previously verified by calculation. As seen in figure 11, for example, for November 13, 1603 UT, the dose rates fall off much faster with decreasing altitude if the secondary neutrons are neglected in toto as indicated by the long dashes (ref. 12) or are in part neglected (ref. 24); the latter is indicated, for instance, at the February 1956 "upper limit" rem and rad dose rates. In reference 12 nuclear interactions are neglected, and in reference 24, although nuclear interactions for primary protons up to 450 MeV were considered, it is assumed that all primaries with energies >450 MeV could be treated as 450 MeV particles. Thus, the more numerous and more energetic secondaries from the higher energy protons, contributing substantially to the neutron cascade, were neglected. The average quality factor Q_F, indicated by the ratio of rem rate to rad rate, increases at lower altitudes because the percentage of neutrons increases.

The amazingly high dose rate, 0.5 to 3 rem/hr theoretically found at SST altitude in the February 1956 event, is supported by the correlation found between the fast neutron flux (1 to 10 MeV) measured at SST altitude and the simultaneous sea-level neutron monitor data during the high-energy event (of very low intensity) of March 30 and 31, 1969. (See refs. 51 and 52.) Figure 12 shows that the neutron increment of 5 percent on the ground corresponds to a dose equivalent rate increment of 90 percent, or about 20 times as much, at SST altitude during the March 1969 event. During the February 1956 event, the neutron increase on the ground was 3600 percent instead of 5 percent; the same factor of 20 then gives a dose rate of ≈ 1 rem/hr at SST altitude. The validity of the Monte Carlo calculations (by using the cross sections of Bertini) is further supported by calculation (ref. 45) of the neutron intensities (1 to 10 MeV) from the proton spectra near the top of the atmosphere during the March 1969 event, which were measured in rockets by Russian scientists. (The alpha-particle content was found to be negligible.) Figure 13 shows these calculated and measured neutron intensity increments, superimposed on the neutrons from galactic cosmic rays, at SST altitude; the agreement is within 20 percent for this event.

Exposure From Solar Cosmic Rays of SST Occupants Without

and With Descent to Lower Altitude

The most important result with respect to exposure of SST occupants obtained from the spectra and calculations is that at cruising altitude (≈ 20 km (65 000 ft)) the internal
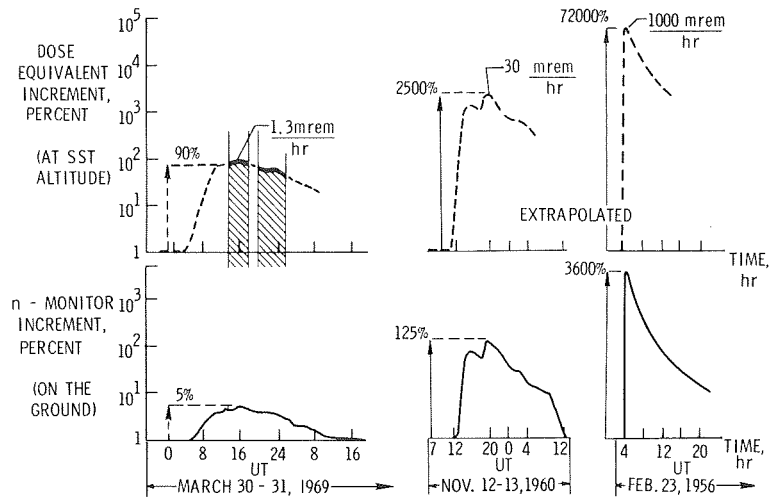
Figure 12.- Energetic solar events measured on the ground and at SST altitudes.
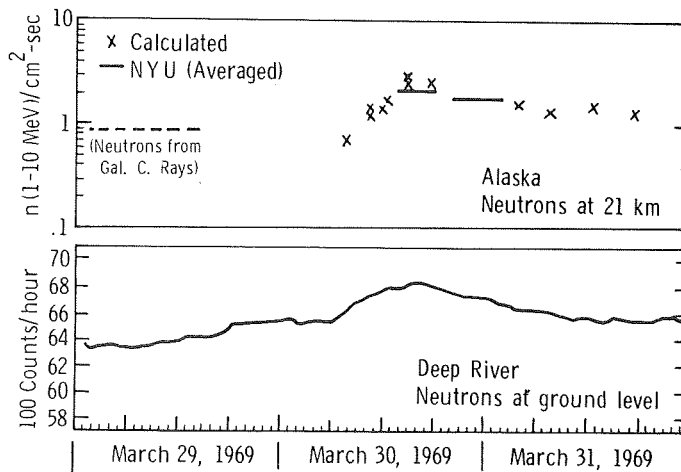
Figure 13.- Comparison of calculated and measured neutron fluxes (1 to 10 MeV) in SST altitudes during the March 30-31, 1969 solar event. The lower curve is the neutron flux history on the ground.

dose rate at the peak of the intense giant-energy event of February 1956 was of the order of 0.5 to 3 rem/hr. Although the giant-energy particle flux falls off very rapidly (see figs. 14 and 15) at such intense high-energy events, the maximum permissible dose equivalent (MPD) of 0.5 rem/1 yr, single or protracted (that is, in either a single or distributed exposure), for individuals of the general population would be exceeded if the airplane continues the flight at cruising altitude.

A second important conclusion can be drawn from figure 11. If at the beginning of such an event, the airplane should descend to an altitude of 9 km (30 000 ft) and continue the flight in this subsonic altitude, the peak dose rate would be between 0.45 and 0.025 rem/hr (depending on choice of the upper or lower limit of the primary spectrum, fig. 10) and the accumulated dose with the prolonged subsonic flight would be below the maximum allowance of 0.5 rem for individuals of the general population. The following table shows how the dose rate would be reduced by descending to lower altitude:

Altitude		Dose equivalent rate, Feb. 1956, in rem/hr	
km	ft	Upper limit	Lower limit
20	65 000	2.9	0.45
15	50 000	1.8	.2
12	40 000	1.0	.1
9	30 000	.45	.025
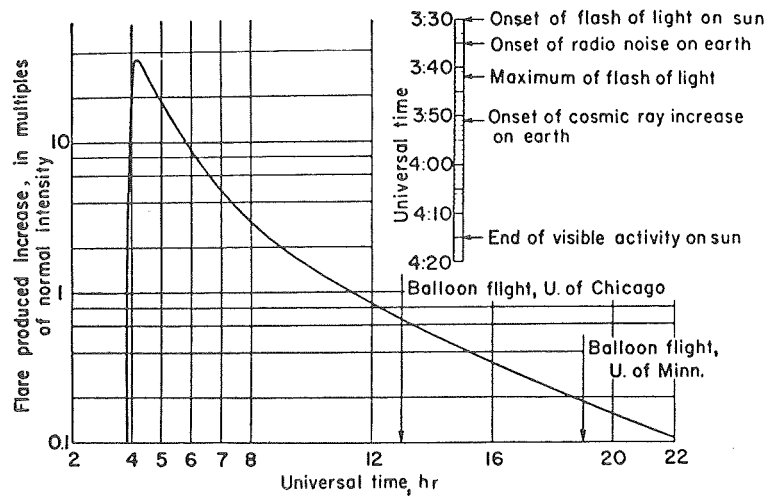
Figure 14.- Cosmic ray neutron surge at sea level during large solar flare of February 23, 1956. Observed by Lockwood et al. at Durham, New Hampshire. (From ref. 4.)

The decay of the dose rate is estimated to occur faster than the intensity profile shown in figure 14 of neutrons at sea level. The reason for this effect is that not only the intensity of the primary particles decreases rapidly in the first hours, but also their average energy corresponding to about the upper and lower limit spectra in figure 10, and with it the penetration power of the charged primaries and secondaries. By assuming the upper limit spectrum to be valid at the peak of the event, the lower limit spectrum is reached after about 2 to 3 hours. According to the preceding table, the dose rate at an altitude of 9 km (30 000 ft) decreases in 3 hours by at least a factor of 18 and not by a factor of about 8 as in figure 14. The decay time τ of the dose rate is then obtained from the equation

$$\dot{D}_p e^{-t/\tau} = \dot{D}_p e^{-3/\tau} = \dot{D}_p \times \frac{1}{18} \quad \text{or} \quad \tau = 0.965 \text{ hr}$$

where t and τ are times in hours and $\dot{D}_p$ the peak dose rate. The integral over any number of hours at an altitude of 9 km (30 000 ft) is then smaller than $0.965\dot{D}_p$ or smaller than 0.45 rem.

Figure 14 (Feb. 1956 event) and figure 15 (other giant-energy events in previous solar cycles, ref. 53), derived from neutron monitor and lead-shielded ion chamber measurements on the ground, illustrate the short duration of the giant-energy particle intensity. With respect to the frequency of such events, it may be emphasized that the February 1956 event was the only such intense giant-energy event that occurred during the $10\frac{1}{2}$ years of the highly active cycle 19. Since the discovery of intense high-energy events in 1942, at most two such events have been observed in one cycle. All other giant events of the past 30 years have been of lower intensity than the February 1956 event, the November 1949 event being the second largest, with about one-half the intensity of the February 1956 event. If the 1949 event was not isotropic, then the intensity in the impact zone may have been larger than is indicated by the measurements outside the impact zone.

During cycle 19 (1954 to 1964), there occurred one intense giant-energy event (February 1956), three medium-energy events of extreme intensity and duration (July 16, 1959; November 12 and 15, 1960), and three somewhat lower energy events of extreme intensity (May 12, 1959; July 10 and 14, 1959). Figure 11 indicates that the peak dose rate at cruising altitude at the November 12, 1960, event (≈2330 UT), the second largest of cycle 19, was only of the order of 30 to 50 mrem/hr in comparison with the 0.5 to 3 rem/hr for February 1956. Thus, these more frequent events, and also low-intensity giant-energy events, are of less concern, even if the same passenger encounters several of these events at cruising altitude.
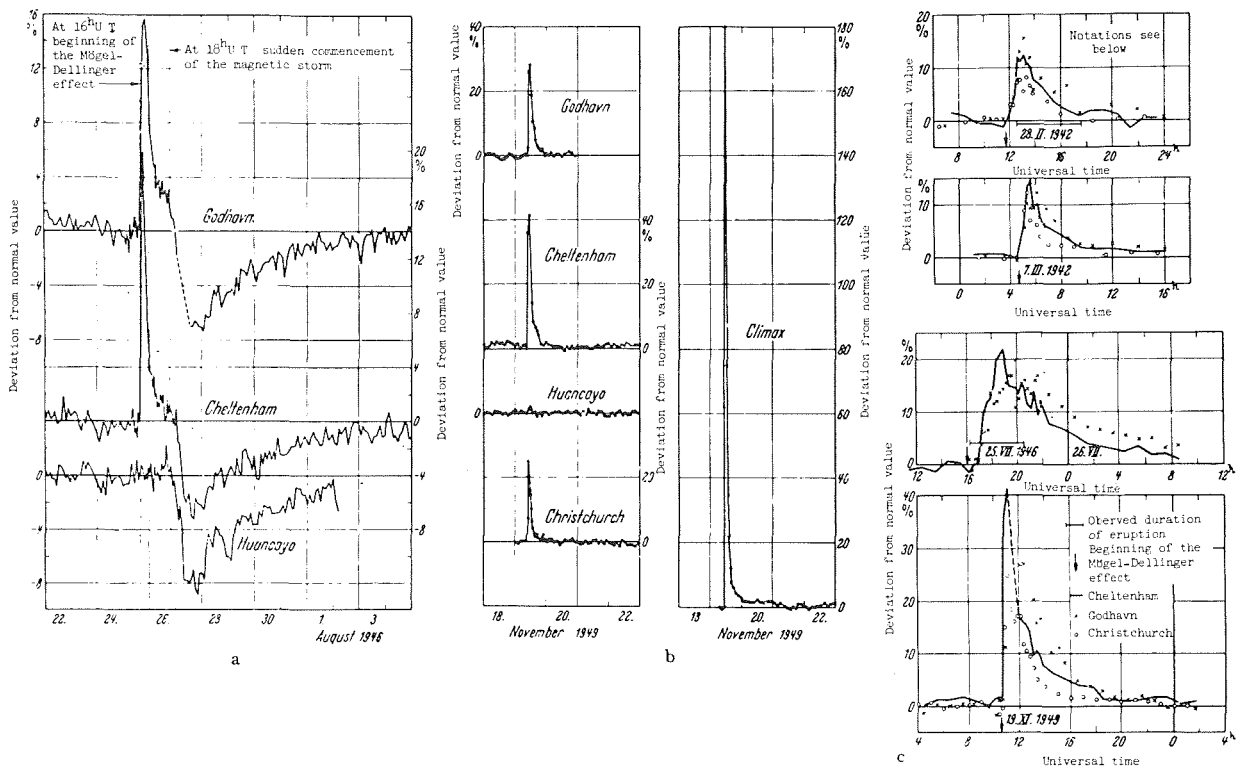
(a) Increase of cosmic ray intensity on July 25, 1946.

(b) Increase of cosmic ray intensity on November 19, 1949.

(c) Increase of cosmic ray intensities during the Sun eruptions of February 28, 1942, March 7, 1942, July 25, 1946, and November 19, 1949 at different stations.

Figure 15.- Intense high-energy solar events from 1942 to 1949; observations with ionization chambers at different stations. Shown is the increase of cosmic ray intensities at ground level measured in ionization chambers covered by 10 cm lead, indicating the meson and electron components produced mainly by solar cosmic ray primaries of very high energy. Unfortunately, neutron monitor data are not available for these earlier giant-energy events. Thus, an exact comparison of high-energy intensities with the February 1956 event intensities cannot be made. For an approximate comparison in the energy range >5 GeV, it may be noted that the increase within the ion chamber at Cheltenham (50° N geomagnetic latitude) was 80 percent in February 1956 (from Dr. Scott I. Forbush), in comparison with 40 percent during November 19, 1949. The figures are taken from reference 53, with permission of the copyright owner.

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Summarizing, it might be said that the solar cosmic radiation seems not to be of significance for the crew, if the crew qualify as radiation workers (this requires that the crew consist of persons over 18 years of age, who are not pregnant, and who carry no prior radiation burden). For radiation workers, 5 rem each year are allowed. The solar cosmic radiation would be of significance, however, for a relatively small number of passengers, if no evasive measures are taken in such rare giant-energy events as that of February 23, 1956.

VI. COMPARISON OF DOSE EQUIVALENTS RECEIVED BY SST CREW AND PASSENGERS FROM GALACTIC PLUS SOLAR COSMIC RAYS WITH MAXIMUM PERMISSIBLE DOSE EQUIVALENT STANDARDS

Maximum Permissible Dose Equivalent Standards

Table II gives maximum permissible dose equivalents (MPD values) for radiation workers and individuals of the general population, as established by the International Commission on Radiological Protection (ICRP). (See refs. 54 and 55.) As seen from table II for radiation workers and for the general population, limits are set for the accumulated dose, as well as for the dose within shorter periods, as 1 year or 3 months (single or protracted), that is, for maximum dose rates.

For a radiation worker the maximum permissible accumulated dose equivalent for the period from age 18 up to age N corresponds to an average of 5 rem/yr. For example, during a 25-year career, he would be allowed to accumulate 125 rem. His maximum dose rate is 3 rem/(1/4 yr) (single or protracted). Thus, it is permissible (but should be avoided, if possible) to receive dose equivalents of 12 rem/yr as long as 5(N - 18) rem are not exceeded.

The general population is a much larger group of people; it includes all those in a population pool, including adolescents below age 18, infants, and pregnant women. The MPD values for the general population are considerably more restricted. The maximum total dose equivalent that may be accumulated up to age 30 is 5 rem; for example, the average dose rate for the years of development and procreation up to age 30 is 0.167 rem/yr (1/30 of the average MPD of radiation workers), and the maximum dose rate is 0.5 rem/1 yr, single or protracted. This 0.5 rem/yr or 1/10 of the average MPD for radiation workers is, therefore, not allowed for each year up to age 30, but only for a maximum of 10 years, if in all other years the radiation burden is negligible. One of the reasons for this restriction to a total of 5 rem to age 30, and to 0.5 rem/yr maximum, is that life in its embryonal or developmental state is much more sensitive to radiation than during maturity. There is, for example, evidence that in utero exposure to a dose as low as 1 roentgen ($\approx$1 rem) causes an observable increase in incidence of embryonal or devel-

opmental damage (prenatal and premature death, keratogenic effects, and leukemia) (refs. 56 to 58), although for animals or man statistical data seem to be insufficient and no dose effect curves for very low doses are available as yet to provide quantitative conclusions. In addition to developmental damage to the individual, genetic damage to the population might be significant in comparison with the natural mutation rate, if all individuals of a population pool and of the follow-on generations should be exposed during their procreative years to higher doses. Exposure of a relatively few individuals (for example, radiation workers) to a 10-fold higher dose (50 rem) in their procreative age than that allowed for the general population would cause their mutation rate to be about double their spontaneous mutation rate, which, nevertheless, is estimated to be an acceptable risk. Such doubling of the mutation rate for a few persons in one generation is estimated to have much smaller genetic consequences for their descendants than the spontaneous mutations of the many previous generations.

The exposures from both galactic and solar cosmic rays of the crew and of various categories of passengers without and with evasive measures are discussed in the following sections and are compared in more detail with the maximum permissible accumulated dose equivalents and maximum permissible dose equivalent rates of radiation workers and the general population. It is assumed that crew members qualify as radiation workers, which implies that they are over 18 years of age, are not pregnant, and accept the risk.

Dose Rates and Accumulated Doses of Crew

In considering dose rates or single brief exposures, the contribution of the galactic cosmic rays is of secondary importance. Solar cosmic ray dose rates at 20 km (65 000 ft) are considerably higher during high-energy events, the value corresponding to the February 1956 event being perhaps as high as 3 rem in a few hours, which would be 100 percent of the maximum permissible for radiation workers, that is, 3 rem/(1/4 yr).

If the aircraft should descend to 9 km (30 000 ft) during the event, an estimate of the upper limit of the mean dose rate for the quarter year is 0.45 rem from the solar flare + 0.15 rem from galactic cosmic rays (see p. 29), or a total of 0.6 rem/(1/4 yr), that is 20 percent of the maximum permissible 3 rem/(1/4 yr). The total for the year would be 1.05 rem in 1956, and less in other years.

If the doses accumulated over a solar cycle, as mentioned before, for the crew are considered, the low-level galactic cosmic radiation contributes more than the solar events. Figure 16 shows, separately, the contribution of galactic and solar cosmic rays to the average dose rate over the solar cycle, as a function of cruising altitude. The given contributions from solar events are maxima; they are obtained by assuming that all the significant events of cycle 19 would have been encountered during their maximum phase for 2 hours, the 2 hours being about the flight time at cruising altitude for high-latitude
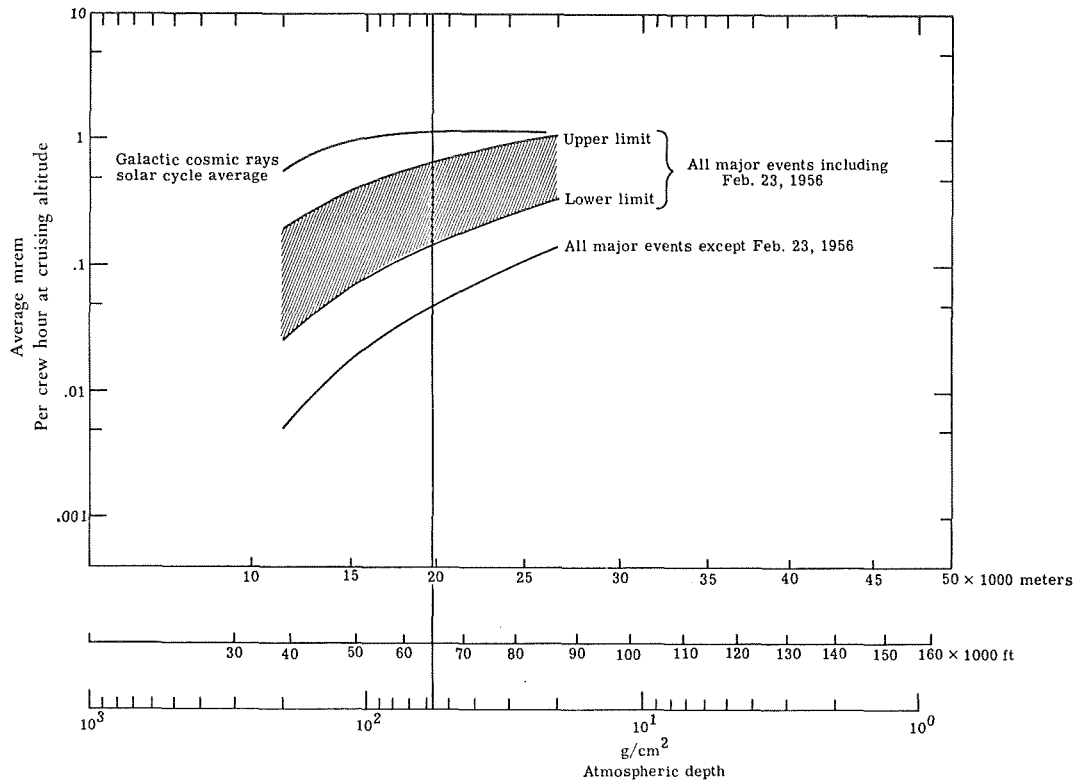
Figure 16.- Internal dose equivalent rates per crew hour from solar cosmic rays received by the crew for encounters with all the major events of cycle 19, in comparison with the galactic cosmic ray dose equivalent rate averaged over solar cycle.

Atlantic routes. The sum of these solar dose equivalents is then divided by 4800, the number of hours at cruise altitude in 10 years, to obtain the solar cosmic ray contribution per cruising hour. As seen from figure 16, the accumulated dose equivalent of the crew at an altitude of 20 km (65 000 ft) would have been, in 10 years, at most $4800 \times 1.2 \frac{\text{mrem}}{\text{hr}} =$ 6 rem from galactic cosmic rays and $4800 \times 0.68 \frac{\text{mrem}}{\text{hr}} = 3.24$ rem from solar cosmic rays or a total of 9.24 rem in 10 years, or $\frac{9.24}{50} = 19$ percent of MPD of 50 rem, the maximum permissible accumulated dose for radiation workers. This calculation assumes that no evasive measures were taken on encountering an event like that of February 1956. If the aircraft descends to 9 km (30 000 ft) and continues at this altitude, the maximum dose equivalent in 10 years would have been smaller by 2.55 rem (the contribution of the February 1956 event would have been at most 0.45 rem instead of 3 rem, see fig. 11 and its discussion). With such evasion, in 10 years 6.69 rem instead of 9.24 rem would have been the maximum accumulated dose equivalent of the crew, or $\frac{6.69}{50} = 13.4$ percent of the maximum permissible accumulated MPD for radiation workers (50 rem). These numbers for crews on high-latitude routes are listed in table III (left-hand side; columns 3

and 4) and might be of special interest with regard to stewardesses who may have retired after 10 years. With descent to 9 km (30 000 ft), the crew receives in 10 years actually only $\lessapprox 6.7$ rem, or an accumulated dose of $\lessapprox 34$ percent more than is allowed for all members of the population up to age 30. Also, the maximum dose rate in the peak year of the 10 years of cycle 19, 0.45 (February 1956) + 0.6 (galactic) = 1.05 rem/yr 1956, would have been only by a factor ≈ 2 larger than the maximum dose per year allowed for the general population.

Nevertheless, it should be noted that the accumulated dose equivalent of the permanent crew members (pilots, navigators, etc) on high-latitude routes is still somewhat larger than the dose that 90 percent of the radiation workers of the nuclear industry actually receive, which is of the order of 0.5 rem/yr or 10 percent of the MPD (ref. 14); the radiation doses received by the crew members can be reduced by assigning them part time to low-latitude or equatorial routes.

Dose Rates and Accumulated Doses of Passengers

The dose equivalents received by passengers depend on the solar events encountered and on their flight time per year, which is presumably, for most passengers, much less than that for the crews. Most of the passengers, it is assumed, would travel less than the equivalent of one round trip to Europe per month (4 hours at cruising altitude). This vast majority of passengers (see table III, right half), which includes nearly all tourists and probably most persons who travel for personal or professional reasons, is considered first.

The large majority of these passengers will not encounter significant solar events because such events are very rare; hence, they will be exposed only to galactic cosmic radiation. They are considered in the upper part of table III, right-hand side. At $\lessapprox 1$ round trip per month, providing ≈ 5 mrem, the dose rate would be $\lessapprox 0.06$ mrem/yr, the accumulated dose would be $\lessapprox 1.8$ rem/30 yr, both dosages being negligible compared with the MPD values for the general population of 0.5 rem/yr and 5 rem up to age 30, or an average of 0.17 rem/yr.

A relatively small number of these passengers may encounter a significant solar event; and it is possible, although improbable, that some may encounter all the events of a cycle such as cycle 19. (See lower part of table III, right-hand side.) Their dose rates from solar events are the same as those that have been found for the crews; however, such rates are much higher percentages of the passengers' maximum permissible dose rate. If they encounter a giant event such as that of February 1956 and the airplane does not descend to lower altitude, they may be exposed to a dose of ≈ 3 rem in a few hours, which is ≈ 600 percent of the MPD of 0.5 rem/yr for the general population and is 60 percent of the maximum allowable accumulated dose of 5 rem for 30 years. Evasion to

TABLE II.- MAXIMUM PERMISSIBLE DOSES (MPD) FOR
RADIATION WORKERS AND GENERAL POPULATION

Exposed group	Condition	Dose, rem
Radiation worker:	Accumulated dose	5 times number of years beyond age 18
Whole body, active blood-forming organs, gonads	Average/year	5
	Maximum/$\frac{1}{4}$ year	*3
Population:	Accumulated dose up to age 30	5
Whole body, gonads	Average/year	0.17
	Maximum/year	*0.5

*Single (that is, in a day, hour, min) or protracted (that is, continuous or fractionated
in 1/4 year or year).

TABLE III.- MAXIMUM DOSE RATES AND ACCUMULATED DOSES OF SST OCCUPANTS COMPARED WITH MAXIMUM PERMISSIBLE DOSE STANDARDS (MPD)

[Cruising altitude 19.5 km (65 000 ft); geomagnetic latitudes >55°; solar data from highly active cycle 19, 1954 to 1964.
Items encircled were excluded from total]

Radiation and dose components	CREW (Flight duty, 80 hr/month) ≈40 hr/month cruising; 4800 hr/10 yr				PASSENGERS ≤4 hr/month cruising				
	Comments	Exposure and percent of MPD for radiation workers			Comments	Exposure and percent of MPD for general population			
	(1 round trip Europe = 2 × 2 cruising hr) / 10 round trips / Month	Dose rate, rem / 1/4 yr	Percent of maximum permissible (3 rem / 1/4 yr)	Accumulated dose, rem / 10 yr	Percent of maximum permissible (50 rem / 10 yr)	≤ 1 round trip / Month	Dose rate, rem / yr	Percent of maximum permissible (0.5 rem / yr)	Accumulated dose, rem / 10 yr	Percent of maximum permissible (5 rem / To age 30)
Galactic cosmic radiation	(≈ 1.2 mrem / Cruise hr) ≈ 5 mrem / Round trip	≈0.15	5%	≈6	12%	Large majority of passengers (No solar events)	≤0.06	12%	≤0.6	12% in 10 years
Solar cosmic radiation	≤ All solar events					Relatively few passengers ≤ All solar events				
February 1956 event	(a) Without evasion	≤3	100%				≤3	600%	60% of permissible 30-year dose	
	(b) With descent to 30 kft	≤0.45	15%	≤0.45	0.9%		≤0.45	90%	≤0.45	9%
Other events, 1959 and 1960	In cruising altitude	≤0.12	4%	≤0.24	0.5%		≤0.12	24%	≤0.24	5%
Galactic + solar cosmic radiation (Cycle 19)	(Feb. 1956, descent)					Relatively few passengers (Feb. 1956, descent)				
Maximum dose rates	Year 1956, Years 1959 and 1960 Other years	≤0.6 ≤0.27 ≤0.15	20% in 1 9% in 2 5% in 7 } of 10 years				≤0.51 ≤0.18 ≤0.06	102% in 1 36% in 2 12% in 7 } of 10 years		
Maximum accumulated doses				<6.69 (In 10 years)	13.4%				≤1.29 (In 10 of 30 years) The maximum doses increase very slowly with more round trips (5 mrem each)	26%
1	2	3		4		5	6		7	

subsonic altitude reduces the February 1956 event contribution to $\lesssim$0.45 rem. Thus, if evasion is made mandatory in such rare cases, and the doses received during the 12 round trips during the year without other major events are added, the dose rate for this year would have been $\lesssim$0.51 rem/yr, which upper limit is just of the order of the maximum permissible dose rate for single years (0.5 rem/1 yr) for an individual of the general population. For those passengers who had also encountered all other significant events of the solar cycle, the maximum dose rates in two other years (1959, 1960) would have been $\lesssim$0.18 rem/yr or 36 percent of the MPD 0.5 rem/yr, and in the other 7 of the 10 years the average rate would be about 0.06 rem/yr, or 12 percent of the MPD.

Concerning the accumulated doses in cycle 19, it may be seen from table III that these other significant events encountered in cruising altitude, in addition to the event of February 1956 in subsonic altitude and $\lesssim$12 round trips, add up to $\lesssim$1.29 rem/solar cycle, or $\lesssim$26 percent of the maximum permissible accumulated dose of 5 rem in 30 years. Thus, even for the very improbable case that all events of three solar cycles such as cycle 19 would be encountered by the same person, who does not make more than 12 round trips per year, the MPD of 5 rem in 30 years would not be reached if evasive measures are taken during giant events.

The remaining passengers are those who fly so often that their exposures exceed the MPD values for the general population, for example, those who may fly as often or more often than the crews ($\gtrsim$120 round trips/yr) or fly more than 12 round trips per year in a giant-event year (as 1956) or more than 76 trips per year (0.38 rem) in other solar active years (as 1959, 1960), as may be the case for executives or controllers of airlines, or diplomats and messengers. It can be assumed that such passengers are over 18 years of age, not pregnant, or otherwise ineligible to qualify as radiation workers.

Actually, SST occupants flying for one solar cycle as often as the crew would accumulate doses ($\lesssim$6.7 rem) only slightly above the maximum permissible limit for the general population (5 rem/30 yr). If passengers fly more often, their maximum dose increases only slowly (5 mrem/round trip) because all solar events are already taken into consideration.

The previously mentioned somatic congenital or developmental damage to individuals should be distinguished from genetic damage (by radiation-induced mutations) to a population pool or to the world population, which is also taken into consideration in the ICRP recommendations (average $\leq$5 rem/30 yr for each individual of the population). A significant contribution to such genetic damage cannot be expected from extended SST travel of several generations, because the contribution of all SST occupants to the maximum permissible genetic dose of a whole population is extremely small.

To illustrate this, a population pool of 300 million individuals and 2000 North Atlantic crossings per week with 100 passengers each may be assumed. The frequency of passen-

ger trips would then be 50 weeks $\times$ 2000 trips/wk $\times$ 100 passengers = 10^7 passenger trips/yr or 3×10^8 passenger trips/30 yr; that is, each member of the population could have made one trip in 30 years. The average dose equivalent *per passenger trip* from galactic cosmic rays may be 2.5 mrem (2 cruising hours) or for all occupants:

$$3 \times 10^8 \times 2.5 \times 10^{-3} = 750\ 000\ \text{rem}/30\ \text{yr}$$

Solar cosmic rays (essentially giant events) could, however, at 300 flights per day or presumably less than 150 airplanes in cruising altitude during such events, contribute even without evasive measures only

$$150\ \text{aircraft} \times 100\ \text{passengers} \times \frac{3\ \text{rem}}{\text{Passenger}} = 45\ 000\ \text{rem}/10\ \text{yr}$$

since only one such event is observed to occur in 10 years, or $\approx$135 000 rem/30 yr. The sum of galactic and solar cosmic ray dose equivalents of all occupants is then 900 000 rem/30 yr, compared with the maximum permissible dose for the whole population of $3 \times 10^8 \times 5$ rem/30 yr = 1.5×10^9 rem/30 yr. SST occupants would thus contribute only 0.06 percent of the maximum dose allowance of each generation.

A recent comparison of the population dose from extensive SST travel (77×10^6 passenger hours/yr for population of United States) due to galactic cosmic rays with that from other sources has been made by Hermann J. Schaefer. On the basis of the new altitude profiles for galactic cosmic rays at sunspot minimum in figure 7 of this paper (see also refs. 40 to 42), Schaefer obtained the result that the SST contribution would be 2×10^{-3} of the contributions of natural radiation on the ground (110 mrem/yr), of medical X-rays (55 mrem/yr), and of fallout (10 mrem/yr); solar cosmic rays and their effects are not treated in this paper. (See ref. 59.)

VII. SAFETY MEASURES

From the estimates of the February 1956 doses, it appears that provisions for timely evasion during such events have to be made to avoid, in particular, damage to pregnant occupants and infants. A body depth dose of the order of 3 rem or 600 percent of the MPD appears to be unacceptable. It might also be mentioned that even if subsequent developmental damage to the fetus or infant cannot be definitely attributed to radiation, the carrier may face legal action if no evasive measures were taken and no proof is provided showing that the actual exposure did not exceed accepted levels. With extensive SST air travel, several thousand passengers may be at cruise altitude when such a giant-energy event occurs.

The most practical and economical evasive measure seems to be timely descent to subsonic altitudes. Such timely descent requires an in-flight warning to the pilots.

For the Concorde, the British and French control agencies require that onboard instruments monitor the dose equivalent rate, including that due to neutrons; the instruments will thus be able to indicate when to descend, and they may be supplemented by recorders to determine the actual exposure.

It may also be possible to supplement or replace onboard instruments by a satellite warning and monitoring system. From sufficiently exact measurements of the primary proton and α-energy spectra in satellites, outside or at the boundary of the magnetosphere, the dose rates and doses of the complex radiation in the airplanes might be derived[8] by satellite or ground-station computers and relayed through conventional channels to the pilots. Since the high-energy particle flux reaches its peak in a very short time during such high-energy events (in the February 1956 event, the peak was reached in 20 minutes), and since the peak dose rate needs to be avoided, the reduction of data, the input of magnetospheric corrections and ground data, the dose equivalent calculations, and the communications with the airplanes en route would have to be performed in approximately real time. Such satellite monitoring systems with established reliability could replace the many radiation instruments and recorders in a fleet of airplanes (instruments requiring permanent maintenance, while actually being needed only at a few unpredictable times during the 10 to 11 years of the solar cycle).

Data from monitoring stations on the ground (for example, neutron monitors, riometers) alone would not be sufficient to determine the dose equivalent rates at flight altitudes with satisfactory accuracy.

Another means of avoiding high-energy events might be to ground or reroute the airplanes before take-off in the event that solar events are predicted within the next few hours. Solar-activity forecasting and monitoring centers, however, might not be able to predict with certainty whether solar particles will occur at all, much less the time within a few hours and the size and the energy spectra of the events. Only intense, giant, or at least high-energy, events are of significance for the SST occupants. These events occur very seldom among relatively more frequent but insignificant low-energy events and high-energy events of low intensity (of which there were about 60 during cycle 19). Therefore, most alarms might be false alarms and this approach might result in many costly and unnecessary grounding or rerouting measures.

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[8] It is presupposed that the cross sections for secondary, especially neutron, production by energetic p, α, and heavier nuclei in air will have been reliably measured at that time, as they are necessary to calculate the dose equivalent rates at the SST altitudes; furthermore, the directional distribution of the radiation has to be measured in the satellites, and disturbances and asymmetries of the magnetosphere have to be taken into account to calculate the dose distribution in the impact zones with sufficient accuracy.

VIII. SUMMARY OF ESTIMATED DOSE EQUIVALENTS AND RADIATION SAFETY IN COMMERCIAL SST OPERATIONS

The results of these measurements and calculations applied to commercial SST operations are

(1) Without evasive measures, for the February 1956 giant event:

The crew dose equivalent rate, averaged over the highly active solar cycle 19 (1954 to 1964), from galactic and solar cosmic rays for 40 hours/month at cruising altitudes in high latitudes, neglecting ascent and descent, would have been $\leqq20$ percent of the maximum permissible accumulated dose (MPD) of 5 rem/yr established by the ICRP for radiation workers; 12 percent is due to galactic cosmic rays.

For the relatively very few passengers who would encounter a rare intense giant-energy solar event such as that of February 23, 1956 at cruising altitude (they may nevertheless number 2000 or more), the MPD/yr for individuals of the general population would be exceeded for that particular year. It is estimated that the dose equivalent rate within the passengers' bodies at cruising altitude during the maximum phase of this most intense giant-energy event observed in 30 years would have been between 0.5 and 3 rem/hr. Such exposure should be avoided, especially with regard to possible damage to pregnant occupants and infants. Events of this kind are observed to occur at most one or two times during an 11-year solar cycle. For other even more intense but less energetic events in other years (for example, 1959 and 1960) of solar cycle 19, the dose rates would have been only of the order of 10 to 50 mrem/hr at cruising altitude.

(2) With evasion by descent to ≈9 km (30 000 ft) altitude at the beginning of a giant-energy event like that of February 1956 (see also table IV):

The crew encountering all other solar events at cruising altitude could have been exposed during cycle 19 on high-latitude routes to a dose equivalent rate, averaged over the solar cycle, of $\leqq0.67$ rem/yr or ≈13.5 percent of the average MPD for radiation workers.

The dose equivalent received by the large majority of the passengers encountering no significant solar events, even if they make two North Atlantic crossings per month, would have been negligible ($\leqq0.06$ rem/yr) in comparison with the individual maximum permissible dose of 0.5 rem/1 yr. For the relatively few passengers who are in flight during an event like that of February 1956, the exposure would also be within this limit, provided that the SST airplanes in high-latitude routes descend to an altitude of 9 km (30 000 ft). Although two events of such size and energy have not been observed to occur in the same year, such passengers may be advised not to fly again in the same year except during solar quiet periods in order to stay within 0.5 rem for the specific year in question. These results are summarized in table IV.

TABLE IV.- DOSE EQUIVALENT RATES IN COMMERCIAL SST

[With descent to subsonic altitude during giant events]

Individual	Exposure from solar and galactic cosmic rays, high-latitude routes	Percent of maximum permissible dose, percent MPD
Crew: (Encountering all solar events) average over solar cycle	≈0.67 rem/yr	≈13 percent of MPD for radiation workers (5 rem/yr)
Passengers: Large majority: No large solar events Up to 2 Atlantic crossings/month	Negligible ≲0.06 rem/yr	≦12 percent of MPD for general population/1 yr (0.5 rem/yr)
Relatively few passengers: Encountering giant events at 9 km (30 000 ft)	≲0.45 rem/yr	≲90 percent of MPD in 1 of 10 years
All other events in cruise altitude	<0.24 rem/cycle	<25 percent of MPD in 2 other single years

If the maximum permissible accumulated dose, say, for 30 years of 5 rem for individuals of the general population is considered, even passengers who would have encountered the giant events at an altitude of 9 km (30 000 ft) and all the other solar events at cruising altitude, and had regularly flown the equivalent of two North Atlantic trips per month for 30 years, would have received at most only 78 percent of this 5-rem allowance. It is assumed that the solar activity in the three cycles is less than, or at most, equal to that during the highly active cycle 19.

Regarding the genetic risk for a population pool, the results confirm that even extensive SST travel would contribute only a negligible fraction (<0.1 percent) to the maximum permissible genetic dose equivalent for the whole population.

On the basis of the presented data, the following conclusions are drawn:

(1) If the suggested precautionary measure of timely descent or other evasive measures can be taken in case of intense giant-energy solar events, radiation exposure for crew and passengers is, in general, substantially below the internationally accepted exposure limits for radiation workers and the general population. On rare occasions

(once in 10 years), while encountering a giant solar event, the exposure limit of 0.5 rem/yr for the general population may be reached in that particular year.

(2) If this evasive measure can be taken, that is, if a radiation monitoring system exists which enables the pilots to descend in time to subsonic altitudes and if the pilots can reach the next airport at subsonic altitudes, cosmic radiation will only in very rare cases interfere with the normal operation of SST aircraft.

For summaries on the radiation measurements and estimated doses in high-altitude airplane traffic, see also references 51 and 52.

IX. OVERALL RESULTS OF THE LANGLEY-NEW YORK UNIVERSITY HIGH-ALTITUDE RADIATION STUDY AND UNSOLVED PROBLEMS

It may be useful to conclude this paper with a survey of scientific results of the NASA Langley-New York University high-altitude radiation study which is not completed. The principal objectives of the study were to obtain worldwide distributions of atmospheric neutrons[9] and of dose equivalent rates at high altitudes and of their variations with solar activity.

From August 1965 to June 30, 1971, 18 balloon flights up to an altitude of 43 km (140 000 ft) and over 250 high-altitude airplane flights were conducted, from the poles to the equator mostly in high latitudes, during different phases and degrees of flare activity of the solar cycle, carrying a tissue equivalent ion chamber and a fast neutron spectrometer. The measurements were supplemented by Monte Carlo nucleon cascade calculations done independently at Langley and Oak Ridge and more recently at New York University to obtain a more complete description of the secondary neutron fluxes and dose equivalent rates as functions of altitude, latitude, and solar modulation and flare particle spectra. The results obtained so far elucidate the important role that fast and energetic neutrons play through the contribution to the radiation doses at jet altitudes; they, furthermore, yielded new data on the leakage rates of neutrons out of the atmosphere, a fraction of which are trapped in the Van Allen belt after decaying into protons, on characteristics of solar modulation of galactic cosmic rays, and on the time-dependent worldwide radiocarbon production within the atmosphere.

The following section will also discuss some unsolved problems, such as the products of reactions of heavy nuclei with matter and developmental damage caused by low

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[9]The processes of production and transport of neutrons in the atmosphere and their products, for example C^{14}, have interested investigators ever since the pioneering paper of Bethe, Korff, and Placzek (ref. 60) in 1940. As director of the Cosmic Ray Project of New York University, Korff has continued his experimental observations first with slow neutron detectors and, since 1962, with a fast neutron spectrometer designed by Mendell and Korff (refs. 38 and 61), which was improved and used during this study.

doses, whose solution is relevant to a more complete understanding of the high-altitude and space radiation environments and their effects, and would also contribute to an understanding of other space problems.

Results for Years 1965 to 1969

This first phase of the program was mainly to determine maximum dose equivalent rates at jet altitudes and to determine quantitatively the contribution of fast and energetic neutrons. The balloon experiments in high latitudes were begun in 1965 to cover the period of the cosmic ray maximum. A group of experiments were repeated yearly through a substantial portion of the solar cycle and later extended at and below supersonic altitudes with airplanes U-II and B-57F to obtain the variation of the maximum neutron fluxes and absorbed dose rates with solar activity. In November 1965 data for other latitudes were also obtained, when the instruments were carried on a 65-hour circumterrestrial flight at an altitude of $\approx$11 km (35 000 ft) with a modified Boeing 707 over both poles. The participation of NASA Langley-New York University on this flight was arranged by Serge A. Korff.

Neutron fluxes and dose equivalent rates in high latitudes.- The measurements in high latitudes fill a gap in knowledge about the intensities and energy spectra of fast neutrons (1 to 10 MeV) produced by cosmic rays, the altitude maximum is at lower altitude and broader, that is, the fluxes at higher altitudes are lower and at lower altitudes considerably higher than theoretically predicted (ref. 20) before that time. The flux decreased by about 40 percent with increasing solar activity during the solar cycle (cycle 20), and the maximum shifted to somewhat lower altitudes. In medium and low latitudes the flux change is less. The flux of 1 to 10 MeV neutrons at galactic cosmic ray maximum in 1965 was found to be 2.46/cm^2-sec at the altitude maximum in 50 g/cm^2 atmospheric depth or an altitude of 21 km (70 000 ft) in 69$^{\rm o}$ magnetic latitude. The neutron differential energy spectrum was found to be of the form $AE^{-1.2\pm0.09}$, where the exponent (slope in a log-log coordinate system) remains within the indicated limits in a wide altitude range (30 to 300 g/cm^2, altitudes of 24 km to 9 km or 80 000 ft to 30 000 ft) during the solar cycle. This relatively flat 1 to 10 MeV spectrum shape turns out to be in agreement with theoretical estimates of Newkirk (ref. 21) and measurements of Haymes (ref. 18) at lower latitudes and is substantially different from the steeper spectrum ($\approx E^{-2}$) found theoretically by Hess, Canfield, and Lingenfelter (ref. 20) or extrapolated theoretically by Patterson, Hess, Moyer, and Wallace (ref. 16, fig. 3) on the basis of measurements of neutrons in different energy ranges in low altitudes and latitudes.

The dose equivalent rate contribution of the neutrons in the spectral range 1 to 10 MeV (which is only $\approx$30 percent of the total neutron contribution) was found to be comparable in magnitude to about one-third of the absorbed dose rate measured simultaneously

in the ion chamber. If one adds the contributions of neutrons of 0.1 to 1 MeV and 10 to 600 MeV energy obtained by extrapolation of the measured spectrum by Monte Carlo calculations at Langley, the total neutron dose equivalent rate obtained for cosmic ray maximum (0.863 mrem/hr) is about equal to the ion chamber dose rate (0.85 mrad/hr) in SST altitudes, or 5 times as much as the percentage that had been estimated in the ICRP task group report (ref. 13, tables 1 and 5) on the basis of theoretical spectra with a steeper slope.

The absorbed dose rate measured in the ion chamber leveled off at an altitude of 24 km (80 000 ft) (30 g/cm^2), increasing from then on only slightly or remaining constant with increasing altitude for all phases of the solar cycle, whereas the fast neutron flux decreases by about a factor of 3 toward the top of the atmosphere (3 g/cm^2). The combined dose equivalent rate exhibits a slight maximum near SST altitudes (20 km to 21 km (65 000 ft to 70 000 ft), 60 to 70 g/cm^2) having the value 1.65 mrem/hr for small tissue samples or body extremities in 1965. At subsonic jet altitude ($\approx$9 km or $\approx$30 000 ft), the dose equivalent rate was found to be lower by a factor of 4.

Theoretical nucleon cascades in the atmosphere. Support of CRAND hypothesis.- Only the 1 to 10 MeV neutrons were measured; however, neutrons with energies between 0.1 MeV and 1 MeV and between 10 MeV and several hundred MeV are also highly biologically effective, and their fluxes were found by Monte Carlo calculations in order to determine the total neutron contribution to the dose equivalent rate from the measurements. In order to obtain the shapes of the entire neutron spectra, the theoretical calculations of previous authors, based on empirical neutron source spectra or considering only the neutrons produced by protons of energy <450 MeV, were replaced by Monte Carlo calculations (see appendix) of the proton and neutron cascades in air for incident protons with energies up to 3 GeV. These calculations used the intranuclear cascade model of Bertini (ref. 26), which yields larger numbers of energetic secondaries than the previously used knock-on model; for incident proton energies between 3 GeV and 10 GeV, the secondary production cross sections of Bertini were extrapolated semiempirically from the lower energy values. If the galactic cosmic proton spectrum is used as input, the derived slope of the neutron spectrum (that is, the spectral index, see table I) in the 1 to 10 MeV range and the altitude profile of these neutron intensities (fig. 5) are in close agreement with the measurements. A most important result is that the low value of this derived spectral index (1.2) is maintained up to neutron energies of 600 MeV and over a broad altitude range; thus, the intensity of energetic neutrons up to 600 MeV is found to be considerably higher (by one or two orders of magnitude) than had been previously estimated. The contribution of neutrons with E > 10 MeV to the total neutron dose equivalent rate was found to be 35 to 40 percent (see fig. 6) and this high percentage persisted down to present jet altitudes (9 km (30 000 ft), 300 g/cm^2). Since the dose rate from charged particles falls off more

rapidly with atmospheric depth, the percentage contribution of neutrons to the total dose equivalent rate is still increasing at these altitudes.

It should be recalled here that in the Langley work, only protons were processed. Although the contributions of the α and heavier primaries are important, their secondary production cross sections are not well known. The absolute values of neutron fluxes and their dose equivalent rates were found by normalizing the calculated neutron intensities to the high-altitude measurements in the 1 to 10 MeV range and by assuming that the heavier primaries do not change the shape of the neutron spectrum substantially, only its intensity. This assumption is probably justified for subsonic to supersonic airplane altitudes. Nevertheless, it is desirable to check the higher energy parts of the neutron spectra and the high dose equivalent rates, which contain the assumption of an altitude-independent spectral shape unchanged by heavier primaries, against measurements with other methods. A comparison with a more direct dose equivalent rate measurement in the same complex radiation environment was possible in situ in the last days of the flight program in 1971, when a highly sensitive LET spectrometer (Rossi type) developed by the Health Physics and Safety Division of the Brookhaven National Laboratory (BNL) under the direction of F. P. Cowan could be flown in the NASA flight package in Alaska along with ion chamber and n-spectrometer. The dose equivalent rates from galactic cosmic rays determined from the measurements with ion chamber and n-spectrometer extrapolated with the Langley code agreed within 15 percent with the dose equivalent rates determined with this BNL LET spectrometer. (See ref. 67.)

Monte Carlo calculations of the energetic neutron spectra and dose equivalent rates on the basis of Bertini's cross sections were made independently by the Oak Ridge National Laboratory (ORNL) Neutron Division (refs. 50 and 62) and later by New York University (refs. 63 to 65). The codes of both institutions for protons were modified to treat also incident α-particles in an approximate manner. The authors confirmed the high relative intensity of energetic neutrons and constancy of the spectral shape over a wide altitude range and extended their calculations to the top of the atmosphere. In agreement with the balloon measurements, it was found that near the top of the atmosphere, the fast neutron spectra are even harder, they were found proportional to $E^{-1.10\pm0.05}$ in the balloon measurements. It may be mentioned here that the albedo neutron spectrum calculated for about 40° magnetic latitude conforms in the energy range up to 100 MeV closely to that observed recently by Preszler et al. (See ref. 66.) These findings besides supporting the theory of neutron production should give new support to the cosmic ray albedo neutron decay (CRAND) hypothesis for the origin of a large proportion of the Van Allen belt protons: previous calculations (for example, ref. 20) could not explain satisfactorily the high intensities of energetic protons in the inner radiation belt. Other strong arguments for the validity of the cross sections and transport calculations are the agreement of the calculated altitude intensity profile and the spectrum of fast neutrons with the mea-

surements, and the relatively good agreement of calculated and measured neutron intensities at SST altitudes produced by an energetic solar flare on March 30 and 31, 1969. The latter arguments have been discussed in more detail in sections V and IX and in the appendix.

Maximum solar event dose rates.- The agreement over a wide altitude range of the measured cosmic ray produced fast neutron spectra and dose rates with the calculations for incident protons up to 10 GeV energy justifies the assumption that one will obtain improved dose equivalent rates by applying the Monte Carlo nucleon cascade calculations to the incident proton spectra of the important giant- and medium-energy events of cycle 19, such as the events of February 1956, and November 12 and 13, 1960, that could not be quantitatively treated before. In the Langley calculations, the assumption was made that the incident particles were protons only. To compensate for high but unknown percentages of α-particles, the "upper limit" proton spectra in space were assumed to be higher, by a factor of 1.5, than those deduced from the increments in ground-neutron monitors, and from balloon, rocket, and satellite measurements. This factor would compensate for the maximum effect that 20 percent α-particles with the same energy-per-nucleon spectrum can have. The obtained value of 3 rem/hr at SST altitude at the beginning of the February 1956 event is thus considered as an upper limit estimate. For the lower energy events, the primary nuclei do not reach SST altitudes or subsonic levels; thus, nearly all the dose equivalent rate increment at an altitude of 9 km (30 000 ft), for example, on November 12, 1960, at 2330 UT, is produced by the deeply penetrating neutrons, according to the new Monte Carlo calculations. The dose equivalent rates at SST altitudes remain in the 30 to 50 mrem/hr range for the most intense medium- and low-energy events of the highly flare-active solar cycle 19 (1954 to mid-1964).

Results for Years 1969 to 1973

The goals of the second phase of the study were (1) to measure neutrons and ionization rates in air during solar particle events in order to compare the secondary neutrons and dose rates calculated from flare particle spectra with the experimental results; and (2) to complete the worldwide survey of the dose rates and neutron distributions from galactic cosmic rays and determine their dependence on solar modulation.

Measured and calculated neutrons and doses during solar events.- Measurements of the ionization and neutron increase at high altitudes during flare events were made with B-57F airplanes in the period 1968 to 1971. Unfortunately, both the low- and high-energy particle events of this period were of very low intensity; hence, the ion chamber dose rate increments were only slightly above the background level in most cases. The airplane operations could not be continued over the descending phase of solar cycle 20, a period for which the most intense and energetic solar events were predicted and in which they actually occurred (August 1972). The dose equivalent rates of the measured events have

been, as yet, only approximately derived. (See refs. 41 and 42.) Further analyses of the ion chamber data and of the incident spectra are required before comparisons between measurements and theory can be made. The analysis of the neutron data is more advanced for the most energetic of the events, that of March 30 and 31, 1969; agreement within 20 percent between the theoretical neutron intensities derived from the incident proton spectra with the Langley code and the neutron increments measured at an altitude of 18 km (60 000 ft) was obtained. (See discussion in section VII and ref. 45.) Similar good agreement was obtained by Mendell et al. with the New York University Monte Carlo code for this energetic event. (See ref. 68.) The incident particle spectra (with low α proportion) are in this case relatively well known from rocket measurements of Russian scientists. For other events, exponential rigidity solar particle spectra fitted by New York University to data from rockets and from Explorer 34 and Explorer 41 satellites and to neutron data on the ground are used as starting points. When the measured fast neutron yields from the lower energy events are compared with the New York University calculations, the measured values are found to be on the average 40 percent to 65 percent lower. (See ref. 68.) Part of the difference between calculation and observation arises because the assumed exponential solar particle spectra do not accurately represent the solar particle fluxes. Knowledge of the incident primary spectra on top of the atmosphere is still insufficient for most events to determine unambiguously whether the Monte Carlo codes overproduce neutrons at primary energies around 50 to 100 MeV or higher.

Global neutron and dose equivalent rate distributions during solar cycle 20. Neutron leakage rates; C^{14} production rates.- As yet, only the altitude profiles of neutron intensities and dose equivalent rates at high latitudes have been presented for different phases of the solar cycle. (See figs. 2 to 8.) The measurements and the theoretical calculations for high latitudes showed that the shape of the neutron spectra ($E^{-1.2}$ to $E^{-1.1}$) changes very little with solar modulation over a wide altitude range; this solar modulation includes periods when the intensity of incident particles is substantially reduced especially in the lower energy range of 100 MeV to some GeV for protons or 460 MV to some GV rigidity. The same low average slope of the fast neutron spectrum and its independence of the incident particle energy were obtained at the aforementioned Earth-encircling flight in November 1965 over both poles at an altitude of $\approx$11 km (35 000 ft) (245 g/cm^2 atmospheric depth) and earlier balloon flights in Hyderabad, India, $\lambda_{magn} = 7^\circ 35' N$ (March 1965) to altitudes of 38 km or 125 000 ft (4 g/cm^2), where the cutoff rigidity for vertical incident particles is about 16 GV — both during galactic cosmic ray maximum. This constant slope, that is, its approximate independence of the energy of the incident particles confirmed for the higher neutron energy range by the Monte Carlo calculations, provides thus an important simplification in any worldwide survey of fast and energetic neutrons and dose equivalent rates, since it is then necessary to

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measure only the fast neutron intensity, for example, in the 1 to 10 MeV range and the absorbed dose rate as functions of altitude, latitude, and solar modulation.

In order to obtain such normalizing data over the globe also for other periods of the solar cycle, further airplane flights with ion chamber and n-spectrometer in the period 1968 to 1971 from Alaska to higher and lower latitudes and up to an altitude of 20 km (65 000 ft) were made, in order to cover the entire span of solar modulation during cycle 20. The first step, the New York University analysis of the neutron data at other latitudes obtained in the years 1964 to 1971 and the calculation of New York University of the neutron spectra down to thermal energies, is complete. The analysis, including the neutron increments during solar events, is published in the June 1, 1973, issue of the Journal of Geophysical Research in three articles under the title, "Time Dependent Worldwide Distribution of Atmospheric Neutrons and of Their Products (1) Fast Neutron Observations, (2) Calculation, and (3) Neutrons From Solar Protons." (See refs. 69, 63, and 68.) Besides the worldwide altitude distributions of fast neutrons at varying degrees of solar modulation from sunspot minimum to sunspot maximum, the articles contain new calculations of the leakage fluxes out of the atmosphere of neutrons up to 400 MeV, and a new estimate of the global C^{14} production rates by neutrons in the energy range 0 to 19 MeV during different periods of the solar cycle and during solar proton events.

The corresponding analysis of the Langley ion chamber data and their integration with the fast and energetic neutron data and theory to a worldwide survey of the total dose equivalent rates at jet altitudes, taking into account solar modulation, is not yet complete. The survey is intended to describe the radiation environments of subsonic to hypersonic airplanes on every route of the globe and for every phase of the solar cycle and degree of flare activity.

Two kinds of Forbush decreases.- Another result concerns the New York University discovery, while comparing the neutron data at altitude for the many background flights in Alaska with the Inuvik sea-level neutron monitor data in the same area, that, at times, the different energy components of the cosmic radiation decline and recover differently from the effects of solar activity. The mean primary response energy of the New York University airborne neutron detector is 1 to 2 GeV per nucleon, the mean response energy of the Inuvik sea-level monitor is 10 to 15 GeV per nucleon. The comparison of the two sets of counting rates during 1968 to 1971 resulted in the identification of two classes of Forbush decreases. Class I consists of large rapid Forbush decreases following solar flares (with profuse injection of MeV solar particles into interplanetary space) in which the low-energy flux is depressed by a smaller percentage relative to the higher energies than would be expected from the solar cycle regression curves of the two detectors. More-over, the low-energy flux tends to remain depressed while the high energies recover and then, when the low-energy recovery does occur, it is more rapid than the high-energy recovery was. Class II Forbush decreases are not associated with solar flares, and the

maximum depression in the sea-level neutron monitors is not reached until several days after the decrease begins. The lower energy primary flux declines and recovers at a rate similar to that observed for the long-term modulation. It is suggested that the causes of class I and II decreases are essentially similar, both being due to quasi-stationary coro- tating plasma structures that differ only in their stage of evolution. The lag in response at lower energies is believed to indicate that the outer modulating region is still in the process of relaxing to its new quasi-equilibrium configuration. These findings and their preliminary interpretation were reported at the 12th International Cosmic Ray Conference in 1971 in Hobart, Tasmania (refs. 70 to 72) and at the 13th International Cosmic Ray Con- ference in 1973 in Denver, Colorado (ref. 73). An analysis of the data, which were gathered over a considerable period of time, is being made. This analysis represents the culmination of a long-term research program and may represent the most significant scientific results on the dynamic structures of the interplanetary medium to come out of this accumulation of experimental data.

Unsolved Problems

Reaction products of incident α and heavier nuclei.- As mentioned before, an important missing link to a better quantitative understanding and prediction of neutron fluxes and dose equivalent rates, or, more generally, of the radiation fields at present and future commercial aircraft altitudes and in space flight, appears to be that the prog- enies of the cosmic heavier nuclei (α, . . ., C, N, O, . . ., Fe, . . .) resulting from their reactions with air and other matter and their differential cross sections are neither theo- retically nor experimentally sufficiently well known to make correct calculations of their contributions to the dose equivalent rates. At the still higher altitudes of hypersonic flight or behind shields in space of equivalent thicknesses, even the heavy primary and heavy fragment fluxes themselves may not be negligible. The work of measuring especially the neutron production cross sections for incident high energy p, α, and heavier nuclei was begun, under a Langley grant, with the Princeton Particle Accelerator, which was the only existing facility modified for acceleration of nuclei up to argon (refs. 74 to 76); however, the program, just after getting underway, had to be terminated because this facility was closed. The problem of calculating the neutron fluxes for incident galactic cosmic rays or for high-energy solar events with high proportions of α-particles, exactly and without sup- port from measurements in the atmosphere, cannot therefore be considered solved. The ability to compute the intensities and spectra within the atmosphere from a known primary flux containing the α-particles would be needed, for example, for the satellite system monitoring the dose equivalent rates in the SST, if this system were to replace onboard instruments. (See section VII.)

Measurements of the nucleon and spallation product cross sections for reactions of α and heavier nuclei in air are only a part of the more comprehensive task of determining

the reactions and transport of incident energetic nuclei and their reaction products in any kind of matter, which has important applications in archaeology, geophysics, astrophysics, space exploration, and biophysics. Such research would not only provide further quantitative information about shielding and radiation safety at high altitudes and in space (in particular, also shielding against the effects of heavy primaries and their heavy fragments in long-term space flights), but would also yield information on the reaction products n, p, T, He, Li, Be, B, . . ., C^{14}, . . . as well as the other nucleides produced in planetary atmospheres and surfaces. The information would be applicable to dating of fossils, moon rocks, and meteorites and, furthermore, would provide clues to the origin of light elements in stellar atmospheres, to trapped radiations (not only around Earth but also around other planets), and to production of transuranium elements. More information would also be obtained about the cosmic radiation itself; for example, from the relative abundances of light fragments emerge clues to the cosmic ray source composition, to the matter that the cosmic rays have passed through, and the age or confinement time of cosmic rays in the galaxy.

The basic experimental and theoretical shielding research, taking into account secondaries, for incident protons has been conducted mainly by the Oak Ridge National Laboratory of the AEC in an 8-year "thick shielding" study sponsored by NASA and AEC. Application to high altitudes and space has also included, since 1968, the assembling of cross-sectional data at Langley and the previously mentioned important first Monte Carlo calculations up to 10 GeV incident energy, in particular of the secondary neutron and proton spectra and the dose equivalent rates; experiments in the Langley Space Radiation Effects Laboratory (SREL) on charged secondaries produced by incident protons and α-particles with 600 MeV energies (150 MeV per nucleon for the α-particles) began to supplement the study with respect to charged secondaries heavier than protons at low incident energies. In the framework of the Langley SST radiation study, work on proton and heavy-heavy interactions for incident energies in the higher energy range was begun simultaneously through grants to the Astrophysics Department, University of Pennsylvania. (See refs. 77 to 79.) The theoretical part of the work, developing nuclear reaction models and computer codes predicting the outcome of heavy-heavy reactions, is at present being continued under Langley sponsorship and cooperation; as previously noted, the essential experimental work has been discontinued.

Developmental damage at low neutron doses.- A second unsolved problem is the effect of low doses of fast and energetic neutrons in in utero exposure of the fetus at different stages of its development. To the knowledge of the authors, no dose effect data exist for fast neutrons in mammals or man, showing, for example, malformation increment as a function of dose in the range from 1 rad to 0.01 rad (nominal 10 rem to 0.1 rem) or lower; experience with such neutrons must be rare, since the energy range is different from that of reactor neutrons. Thus, there seems to be as yet no quantitative information, for the

pregnant SST passenger or for that matter, for the present-day pregnant jet passenger, as to the risk from solar flare events (say, 0.5 rem), except that it is probably small in comparison with the normally occurring malformation rate. A part of the problem is the prenatal death rate at low doses. A first investigation on mammals was recently reported by the FAA Medical Institute in Oklahoma and the Oak Ridge National Laboratory. (See ref. 57.) The authors determined the prenatal death rates of mouse zygotes after doses of fast neutrons and X-rays in the ranges 0.5 to 20 rad and 10 to 100 rad, respectively. The LD 50 (the dose producing 50 percent dead embryos) was found to be 14 and 60 rad, respectively, that is, the RBE (relative biological effectiveness) of the neutrons was found to be about 5 for prenatal death. The survival curve has been extrapolated linearly to lower doses since experiments with protracted irradiation gave evidence that embryo death after irradiation of the zygotes with neutrons was the consequence of a single irreparable lethal injury event (this indicates no shoulder-type survival curve). An excessively large number of animals would be required to obtain statistically significant results at lower doses such as 0.5 rem. The irradiations are applied in the preimplantation period, which is the most sensitive period for prenatal death.

The malformation problem requires different experiments. The organism is known to be most susceptible to induction of malformations in the major organogenesis period after implantation of the egg in the uterus wall. The doses producing a significant increment in malformations may be smaller and the RBE of fast neutrons for such less destructive effects and on larger objects at low doses considerably larger. RBE values of the order of 50 are found at doses of 0.1 to 1 rad of fast neutrons in, for example, chromosome deletions in tradescantia plants. (See ref. 58.) Irradiations of large numbers of fertilized frog eggs in the period of maximum formation of organs with low doses of fast neutrons and X-rays, and analysis of subsequent keratogenic effects, which had been planned in the context of the Langley high-altitude radiation study, should be a practical approach for obtaining statistically significant results.

CONCLUDING REMARKS

Dose equivalent rates produced by galactic and solar cosmic rays are presented as a function of altitude. The dose equivalent rates from galactic cosmic rays and their variations with solar activity were derived by using measurements of the absorbed dose rate with tissue equivalent ion chambers, and of the fast secondary neutrons (1 to 10 MeV) with a phoswich scintillation spectrometer during the years 1965 to 1971 at altitudes up to 41 km (138 000 ft) mostly in high latitudes. To obtain the important contribution of energetic neutrons to the dose equivalent rates, the measured fast neutron spectra in the energy range 1 to 10 MeV were extrapolated toward high and low energies by means of a Monte Carlo calculation of the transport of the nucleons in air at incident primary protons

of energies 0.02 to 10 GeV. The calculation also improves estimates of dose equivalents at intense giant-energy solar particle events, such as that of February 23, 1956, which may produce exposure levels at SST altitudes exceeding internationally accepted standards for individuals of the general population.

The results of these measurements and calculations with respect to commercial SST operations are:

(1) The crew dose equivalent rate, averaged over the highly active solar cycle 19 (1954 to 1964), from galactic and solar cosmic rays for 40 hours/month at cruising altitude in high latitudes would have been $\leqq 20$ percent of the maximum permissible dose rate (MPD) for radiation workers (5 rem/yr). Twelve percent is due to galactic cosmic rays.

(2) The exposure for most of the passengers, who do not encounter solar events and who cross the North Atlantic less than twice a month, is less than 12 percent of the maximum permissible dose rate (MPD) for individuals of the general population (0.5 rem/yr).

For the relatively few passengers who encounter a rare intense giant-energy solar event at cruising altitude, the MPD per year for individuals of the general population would be exceeded for that particular year. Such dose rates might be considered unacceptable, especially for pregnant occupants and infants.

The effectiveness of descending to lower altitudes in the case of giant-energy solar events as inferred from calculations and of other means for avoiding unacceptable doses in commercial SST operations is discussed. If, in such rare cases, the transport descends to subsonic altitude, the exposure limit of the passengers would not be exceeded.

Regarding the genetic radiation risk, the results confirm that even very extensive SST travel would contribute only a negligible fraction (<0.1 percent) to the maximum permissible genetic dose equivalent for the whole population (average allowance per individual of 5 rem up to age 30).

Finally, the most important scientific results of the NASA Langley-New York University high-altitude radiation study, 1965 to 1973, obtained so far, and unsolved problems, are discussed. The high neutron intensities measured in the 1 to 10 MeV range and the flat slope ($\approx E^{-1.2}$) of the neutron energy spectra being theoretically found to continue to neutron energies >400 MeV in a wide altitude and latitude range not only reveal that fast and energetic neutrons contribute substantially to the radiation dose equivalents in jet and SST altitudes ($\geqq 50$ percent), but also by extrapolation of the neutron spectra to low energies with the Monte Carlo method, led to a new determination of the time-dependent worldwide radiocarbon production rates within the atmosphere and of the leakage rates of energetic neutrons out of the atmosphere. Also mentioned is the discovery by New York University scientists, during flight measurements continued over several years, that the high- and low-energy cosmic ray intensities decline and recover differently from the

effects of solar activity during and after certain Forbush decreases; this discovery casts new light on the dynamic structures of the interplanetary medium and on the mechanisms of solar modulation.   Unsolved problems are the contribution of α and heavier nuclei to the secondary cascades in air and the quantitatively unknown keratogenic or other biological effects of low doses of neutrons and heavy nuclei, such as are encountered in high altitude and space flight.   Continued investigations of the reactions of heavier nuclei with matter will bring a more complete understanding of the radiation environments in high altitudes and of the effects of shielding in space, besides being applicable, for example, to dating of moon rocks and yielding clues to the source spectra and age of cosmic rays and the composition of stellar atmospheres.

Langley Research Center,
   National Aeronautics and Space Administration,
      Hampton, Va., July 23, 1974.

APPENDIX

TRANSPORT AND DOSE EQUIVALENT CALCULATION FOR
PRIMARY PROTONS UP TO 10 GeV ENERGY
PENETRATING THE ATMOSPHERE

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This appendix will briefly review the theoretical calculations that are mentioned in the text, which provide dose rate as a function of altitude and of the energy spectrum of the cosmic rays entering at the top of the atmosphere. As indicated in the body of the paper, such calculations not only provide a conceptual framework for understanding the phenomena involved but are, in fact, essential for estimating the higher energy portions of the neutron spectra, since the instruments do not provide information for neutron energies larger than 10 MeV. The present discussion will, in particular, compare the present calculations with some earlier calculations and also with some recent, more nearly comparable, studies.

Transport Calculations

The purpose of the transport calculations is to determine the flux spectra of the primary and secondary components (p, n, μ, π^+, . . .) at flight altitudes, especially for the case of the more energetic high-energy incoming primary cosmic rays. The flux spectra are essential for estimating the dose equivalents, which is the main purpose of the present paper.

Dose equivalent estimates using transport calculations with nuclear interactions have been made since 1962 in shielding studies by Kinney, Zerby, Irving, Alsmiller, and Moran in 1964 (refs. 30, 46, and 47) and, with special application to the SST, by S. B. Curtis in 1965 (unpublished), and Leimdorfer et al. in 1967 (ref. 23). These estimates are uncertain for high-energy events because the cross sections were known during that period only for energies up to about 450 MeV. In addition to this limitation, the calculations of Curtis used the "straight-ahead" approximation and considered only the first generation of secondary particles.

A calculation that considers only the first generation will be of questionable adequacy after one-half mean free path. For instance, the well-known neutron maximum is formed by neutrons which are two and three generations removed from the high-energy primary radiation incident on top of the atmosphere. With particular reference to the present

problem, for isotropic incidence of the cosmic rays, the angle-averaged mean free path is only 35 g/cm^2, which is well above SST altitudes.

The Transport Code

The Monte Carlo code used in the present calculations is a set of computer programs written for the Control Data Corporation (CDC) 6600 computer. These programs record the history of each incident particle and its progeny until they are stopped, absorbed, or thermalized. An analysis program then reads the history tapes and compiles statistics on the fate of each generation of particles. Specifically, the statistics compiled for this study are neutron and proton differential flux energy spectra at various altitudes.

The transport program for energies below 400 MeV was written by Leimdorfer et al. and is described in reference 25. This program was extended to the GeV range by personnel of NASA Langley Research Center. The basic structure of the program is the same as that in reference 25 and is extended to include the transport of pions.

Dose Estimates

The flux spectra obtained from the transport calculations (see neutron flux in fig. 6) were converted to dose rate by using the flux dose rate conversion factors described in the body of the paper. The results of the calculations can be expressed as dose yield functions and are given by Wilson et al. in reference 43. The dose due to all particles other than nucleons has been neglected (for example, pions, electrons, and gamma rays). Their contribution to the absorbed dose is estimated to be small; for example, the absorbed dose due to gamma rays is estimated in reference 43 to be about 10 percent of the neutron absorbed dose. The dose equivalent is not greatly affected because of the low biological effectiveness of these neglected radiations; that is, $Q_F = 1$.

Results and Discussion

As is the case with any calculation based on a theoretical model, one is faced with the ultimate task of evaluating the essential validity of the calculations. The ultimate confirmation of these transport calculations lies in the comparison with experimental observation. Two such comparisons are made at this time for the galactic cosmic rays. In addition, data are given for the time history of a solar event that occurred during cycle 20 in which simultaneous measurements of incident proton flux and atmospheric neutrons were made. First the limitations of these comparisons will be discussed.

The galactic cosmic rays are composed principally of protons and heavier nuclei (most of which are He^4). Of all nucleons incident on the top of the atmosphere, approximately 60 percent are free protons and the remaining 40 percent are neutrons and protons

in bound states. The energy spectra per nucleon are about the same for both and show that approximately 90 percent of all nucleons have energies less than 10 GeV. The heavy nuclei (heavier than He^4) incident on top of the atmosphere lose energy at a faster rate than protons because of their greater charge and they are not as prolific (average number of secondaries per interacting nucleon) in nuclear interactions as free nucleons. It appears reasonable to assume that fragmentation occurs to a larger extent in heavy-heavy interactions. In other words, the contribution of the heavy primaries is confined mainly to the upper atmosphere except for their high-energy nucleonic collision products that are less numerous than the high-energy nucleons produced by primary protons.

For the present calculations, only protons were considered to be incident on top of the atmosphere. The spectrum for galactic cosmic protons at solar minimum as given by reference 48 was used. This spectrum is now known to be too high in the range of 0.1 to 10 GeV. (Compare refs. 48 and 49.) This difference will, in part, compensate for neglect of the heavy primaries in the calculations. The proton spectrum for the March 30, 1969, event as measured from high-altitude rockets was also used.

Results of the calculations are presented in figures 5, 6, 8, 11, and 13. In figure 6 is shown the calculated neutron spectrum (histograms) together with the measured data of Mendell in the range 1 to 10 MeV. The altitude dependence of the neutron flux in the 1 to 10 MeV range, shown in figure 5 (see also ref. 45), is also in reasonable agreement with the measurements. The dose equivalent rates in the center of a spherical phantom, shown by the small circles in figure 8, measured and calculated, again show reasonable agreement. (See also body of paper.)

The calculated average dose in a 30-cm tissue slab is presented in figure 11 for several solar events of cycle 19. These dosages have been compared in reference 40 with the previous estimates of lower limits based on the work of Leimdorfer et al. for protons up to 450 MeV (ref. 24), and with calculations neglecting nuclear interactions (ref. 12). For energies and altitudes where the primaries are still the most important components, all three calculations are in reasonable agreement with respect to the absorbed dose (rad). At larger atmospheric depths, meaningful dose equivalent estimates can be made only by properly accounting for nuclear interactions as seen in figure 11. The reason is that the secondary production cross sections increase rapidly at energies just above the first pion production threshold (E > 400 MeV).

In figure 13, the measured secondary neutrons produced in the atmosphere by high-energy particles associated with the March 30, 1969, solar event are shown in comparison with theoretical predictions using the incident proton spectra reported in reference 80. Corrections have not been applied to the primary proton spectra (the proton spectra used were measured in the Earth's stratosphere), the effect of the presence of α-particles was not considered, and possible background enhancements or Forbush decreases were

not taken into account in making the background subtractions for the experimental measurements. Even so, the agreement with neutron measurements at about SST altitudes is within 20 percent.

In figure 17 are shown the recent calculations for the February 1956 event by T. W. Armstrong et al. (ref. 50) in comparison with the extremity dose of the present calculations. Reference 50 used maximum dose conversion factors for neutrons and skin dose for protons. (The attempt appears to have been to make an upper limit estimate for the extremity dose.) The two calculations of rad in figure 17 agree well for the lower limit spectrum. The upper limit calculations indicate that the primaries in the range 3 to 10 GeV, which were neglected in reference 50, cannot be neglected for this spectrum. When the present calculations were made over the same energy range with the conversion factors of reference 50, the agreement between the two calculations was within 4 percent.

A main result of these calculations is the importance of the high-energy neutrons (greater than 10 MeV) to the dose equivalent (about 40 percent of the total neutron rem rate for galactic cosmic rays) and the role that these high-energy neutrally charged particles play in carrying the dose deep into the atmosphere.
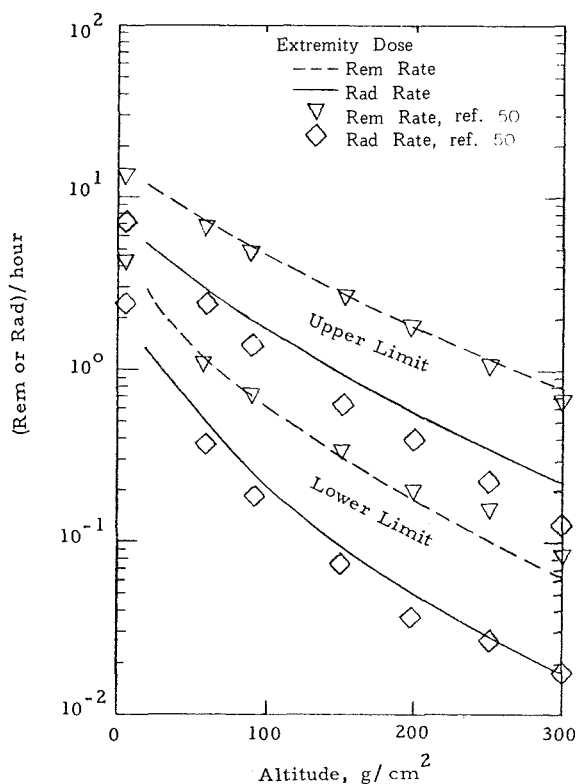

Figure 17.- Calculated upper and lower limits for dose rate in extremities of the prompt spectrum of the February 1956 solar event compared with a similar calculation (for energies <3 GeV) presented in reference 50. Note that these extremity dose rates are about 2 to 3 times the average dose rates in a tissue slab presented in figure 11.

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