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RADIATION EXPOSURE IN SUPERSONIC TRANSPORTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Radiation exposure levels for flight personnel and passengers in supersonic transport operations at altitudes up to 75,000 feet (23 km) are estimated on the basis of recent data, and compared with the maximum permissible exposure levels for normal peacetime operations recommended in 1960 in the guides of the Federal Radiation Council.

INTRODUCTION

The problem of the effects of space radiations on passengers and flight crew in supersonic airplanes, with anticipated operational altitudes up to 23 km, is at present not completely solved nor accessible to an exact quantitative treatment. One reason is that the primary space radiations undergo complicated changes in composition and intensities during their penetration through the atmosphere and build up secondary radiations in the air, in the aircraft, and in men's bodies, the spectra and intensities of which defied, until now, a rigorous analysis. In addition, the biological effects of certain primary and secondary components are not completely known at present. Nevertheless, with regard to galactic cosmic rays, the ionization produced by primaries and secondaries and the composition, energies, and fluxes of the main components have been approximately determined at these altitudes; specifically the over-all ionization and the fluxes of the biologically more effective components have been separately measured. The effects of the latter, except for the heavy primaries, can be roughly estimated on the basis of the biological effects of radium concentrations within the human body that provide the same ionization, as was carried out by Van Allen as early as 1952 (ref. 1). It is intended in the first part of this survey to summarize these approaches, that allow the radiation exposure caused by galactic cosmic rays in supersonic-flight altitudes to be expressed in rem and curie of radium, and to compare the exposure levels, up to 23 km, with the maximum permissible exposure levels cited in the guide lines of the International Commission on Radiological Protection or the U.S. Federal Radiation Council. It may be emphasized that the presented numbers are based on upper limits of particle fluxes and of nuclear collisions per gram

[1]The information contained herein was presented as Paper No. 49 and comments to the questionnaire at the Fourteenth Technical Conference of the International Air Transport Assoc., Symposium on Supersonic Air Transport (Montreal), Apr. 17-21, 1961.

tissue and are thus considered as upper limits of exposure. The biological effect of heavy primary tracks appears, however, understated by replacing them by a corresponding number of α-particle tracks in line. A safety factor 10 in the radium equivalent is therefore provided.

The knowledge on radiation in the environment of the earth and within the atmosphere has increased substantially in the last years. Besides galactic cosmic rays, solar cosmic rays have been discovered and are, at present, under exploration. These solar cosmic rays, associated with flare eruptions on the sun, are mainly transient proton streams that can, in some cases, penetrate deep into the earth's atmosphere. Their characteristics and implications to supersonic transport flights are considered in the second part of this survey. Since the spectral intensities of these protons fall off more steeply with higher energies than those in the case of galactic cosmic rays, the buildup of secondaries is less pronounced. For approximate dose rate calculations, therefore, a straightforward approach is used in which the primary protons are assumed to be attenuated by electronic collisions only, with nuclear collisions and secondaries being neglected.

The Van Allen belt radiations and aurora radiations are not treated in this report. Belt particles can reach the uppermost atmosphere in northern latitudes during geomagnetic storms; the primary radiations or the soft X-radiations, the latter produced by belt electrons during such events within the highest atmosphere, as well as aurora radiations can, however, not penetrate to the relatively low altitude of 23 km. The overhead air layer of 36 g/cm^2 is sufficient to attenuate these low-energy radiations to practically zero intensity.

Symbols and definitions of radiological dose units and terms are given in the appendix, which contains also the protection guides for normal peacetime operations recommended by the Federal Radiation Council. The formerly used unit 1 rep = 93 ergs/g, retained in some figures of this report, is replaced in the text and the tables by the now generally used unit 1 rad = 100 ergs/g. The difference of 7 percent in the numbers is not considered significant in the light of present uncertainties.

GALACTIC COSMIC RAYS

Composition and Intensities, Space Distribution and Time Variations, and Penetration

Comprehensive information about the physics of cosmic rays is available in the standard collective works of Wilson and Wouthuysen (ref. 2), Heisenberg (ref. 3), Rossi (ref. 4), Montgomery (ref. 5), and Peters (ref. 6). In addition to the IGY satellite reports and the original literature, recent data have been summarized by Winckler (ref. 7) and Simpson (ref. 8). Only a brief survey is given in the following paragraphs.

The primary galactic cosmic ray beam consists mostly of protons, α-particles ($_2He^4$ nuclei), some intermediate nuclei C, N, O, . . ., $_{20}Ca$, and a few heavier nuclei observed up to Sn (Z = 50), stripped of electrons, with energies of the order of 50 Mev per nucleon to extremely high energies of the order of 10^{12} Mev. The composition is approximately 85 percent protons, 13 percent α-particles, and 2 percent heavier nuclei. (See ref. 7.) The particle flux in the distant environment of the earth outside the geomagnetic field is isotropic; that is, the particles arrive with equal intensity from all directions of the galaxy. The number of particles per unit area per second decreases with increasing energy. The over-all value of the flux of cosmic ray particles is low. During solar maximum activity years, outside the geomagnetic field, the flux (solid angle 4π) has been measured as 2.5 particles/cm^2/sec (ref. 9). The ionization rate measured with a thin-walled ionization chamber (ref. 7) amounts to 0.1 roentgen/week, or 14.3 mr/24 hr during solar activity years. For a rough comparison it may be mentioned that the maximum permissible continuous exposure rate for radiation workers according to the guides presented in reference 10 is of the same order of magnitude, that is, 0.1 rem/week.

In the earth's magnetic field, the charged particles are deflected in such a manner that low-energy particles cannot reach lower latitudes because they are cut off by the geomagnetic field except in regions near the geomagnetic poles. For this reason the intensity decreases from the poles to the equator at the same altitude. It decreases by a factor of about 20 during solar maximum years at an altitude of about 30 km, as demonstrated in figure 1. The ionization within the upper atmosphere is higher by a factor of about 2, in higher latitudes only, during the 1 to 2 solar minimum years than during the period of higher solar activity (approximately 9 years).

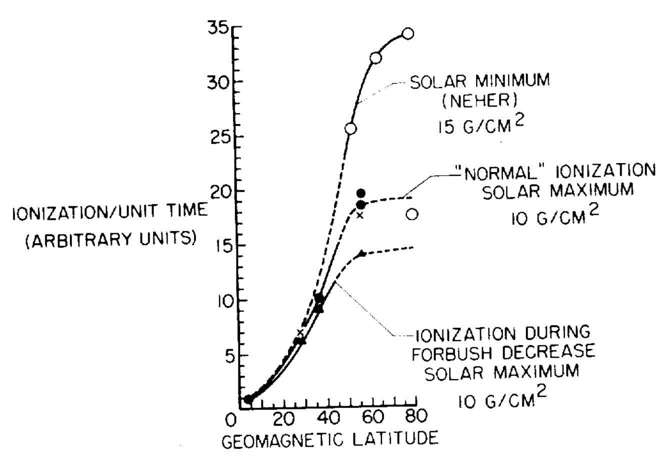

Figure 1.- Total ionization at atmospheric depth of 10 g/cm^2 as a function of geomagnetic latitude at solar minimum and maximum. (From ref. 7, J. R. Winckler.)

From the latitudinal distribution of the galactic cosmic ray intensity in the high atmosphere, it is concluded that only the polar regions need be considered in estimating upper limits of radiation exposure. More specifically, during solar maximum years, the regions beyond 55° magnetic latitude would be considered, since in these years the cosmic ray intensity does not substantially increase either farther north or south.

The variation of the particle flux with altitude, for example, its increase up to about 18 km (60,000 feet, or residual atmospheric depth of ≈75 g/cm^2), is shown in figures 2 and 3. This increase is followed

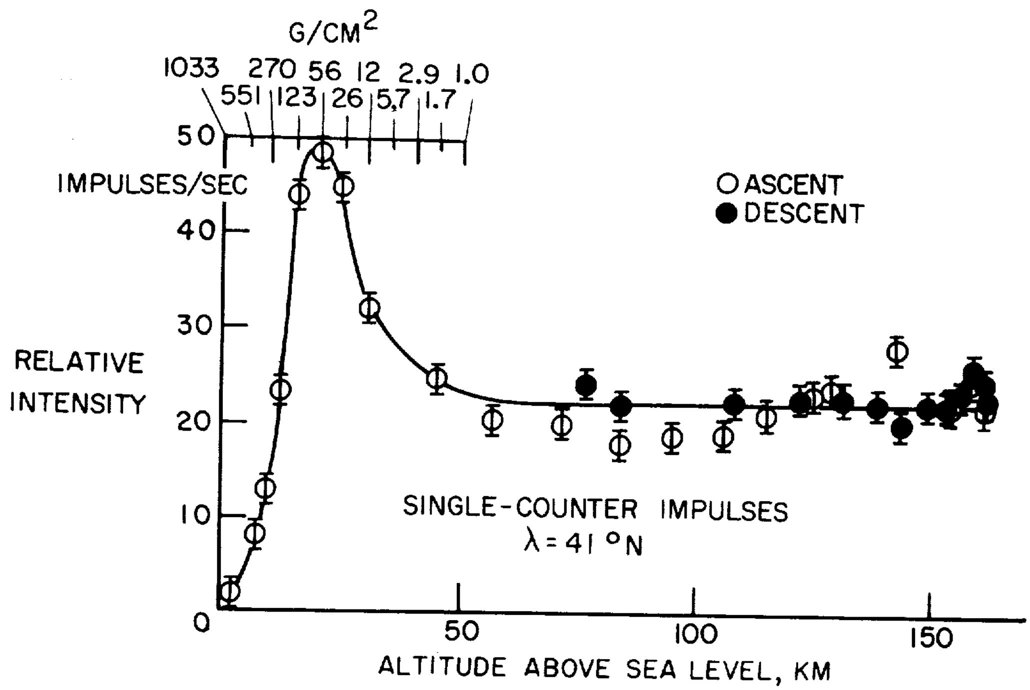

Figure 2.- Total intensity up to very high altitudes measured by unshielded single counter in medium latitudes. (From ref. 11, J. A. van Allen and H. E. Tatel.)

at higher altitudes by a decrease of particle flux. This so-called "transition effect" is caused by nuclear collisions of primaries with nuclei of the atmosphere producing high-energy secondaries, which multiply in further collisions. The secondaries that are produced in this way are mainly protons, neutrons, α-particles, mesons, electrons, and photons of increasing number. The heavier primaries especially, impinging on top of the atmosphere, degrade in these collisions with respect to mass and charge into more lightly ionizing secondaries during their penetration deeper into the atmosphere. Figure 3 shows the change of the composition

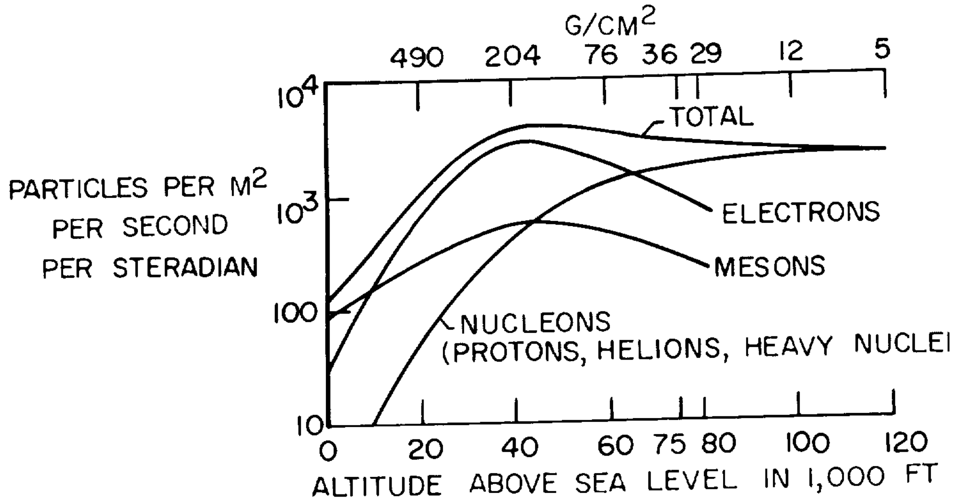

Figure 3.- Altitude profile of particle transition of cosmic ray beam in the atmosphere. (From ref. 12, H. J. Schaefer.)

of the cosmic ray beam with altitude. Indicated are the three main components: the nucleonic component, the electronic or soft component, and the μ-meson or hard component. At an altitude of 18 km (60,000 feet), the flux of nucleonic particles is already smaller than that of electrons. Electrons and μ-mesons are light ionizing particles which interact only very slightly with nuclei and thus produce no heavier secondaries in air or condensed material. Up to this altitude, the biological effects of galactic cosmic radiation in an airplane can be approximately estimated by measuring the ionization in rad in a thin-walled ionization chamber by taking into account secondaries produced in the surrounding material and in the human body by a factor 2 or 3 and considering this ionization as biologically equivalent to the same ionization produced by X-radiation. (See ref. 1.) The prevailing lightly ionizing radiation up to these altitudes has no higher relative biological effectiveness (RBE factor, see appendix) than one.

With increasing altitude the nuclear component increases and an increasing incidence of nuclear collisions[2] occurs in air or material exposed to the radiation because of the abundance and the interactions with matter of the nuclear primaries and high-energy nuclear secondaries. In these nuclear collisions, in addition to energetic secondaries of low specific ionization - the carriers of the nucleonic or photoelectronic cascades mentioned previously - several low-energy (≈10 Mev) protons, neutrons, and α-particles (evaporation particles) are produced. This

[2]Also called nuclear bursts or "stars" because the collision products spread out to all sides.

latter low-energy nucleonic component if produced in the human body is of special importance with respect to biological effects, because the charged low-energy particles and recoil nuclei of neutron collisions have high specific ionization and thus a high biological effectiveness. A second component of high biological effectiveness is the heavy primaries, if they come to rest by electronic collisions. Of course, the frequency of such events is low. The intensity of heavy primaries is rather rapidly attenuated by electronic and nuclear collisions in the first 30 g/cm^2 of the atmosphere or at supersonic-flight altitudes.

According to the concept mentioned in the introduction, the effects in an airplane at supersonic-flight altitudes of the over-all ionization dosage, to which all components contribute, of the heavier ionizing particles, and of special phenomena such as showers are treated separately in the following sections, and are added up in terms of maximum permissible ionization dosage or content of radium insofar as these terms appear applicable.

Over-All Ionization Dosage Produced by Galactic Cosmic Rays

Figure 4 shows two altitude profiles of ionization in northern latitudes measured within a Neher ionization chamber during maximum and minimum solar activity. The profiles are selected out of a collection of

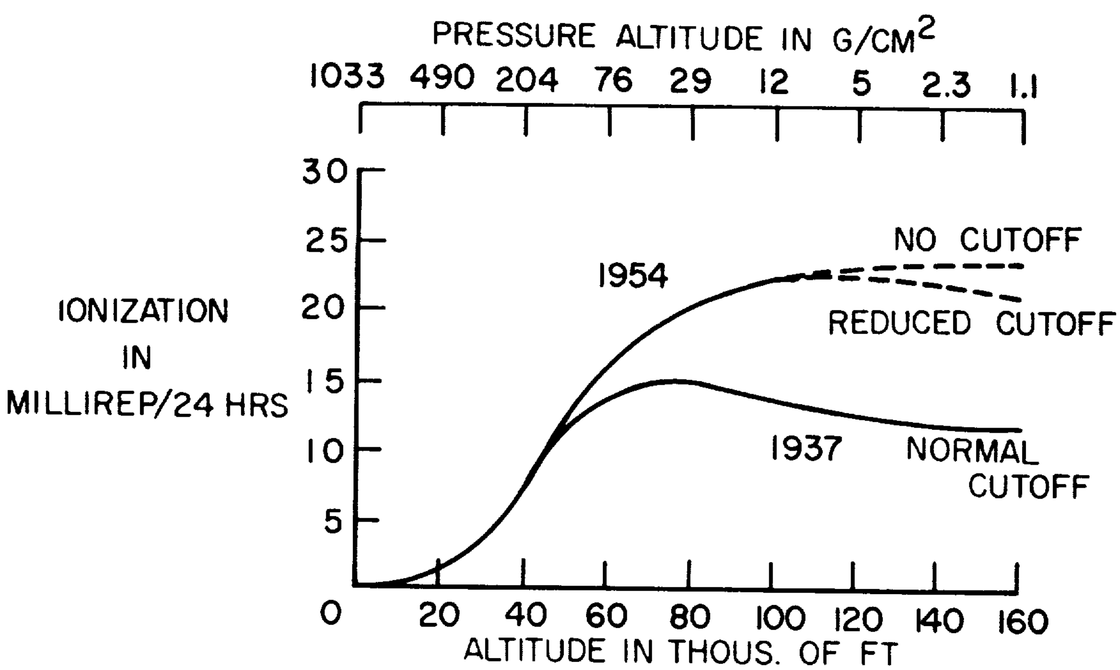

Figure 4.- Altitude profile of the total ionization in a year of high (1937) and low (1954) solar activity. (From ref. 12, H. J. Schaefer.)

data over a period of more than 20 years presented by Neher (refs. 13 and 14). On the basis of the measurements of the increase of secondaries under thick layers of material and of star frequency with altitude, Van Allen (ref. 1) has suggested a factor 3 to 4 as a reasonable maximum for the increase of the physical ionization dosage in rep/day or rad/day at highest altitudes. This increase is due to secondaries produced under thicknesses of several centimeters of lead and aluminum and in the human body, including the contribution of star secondaries.

From figure 4 and on the basis of the factor 4, which should be considered as an upper limit, the following ionization is obtained at an altitude of 75,000 feet (23 km):

During solar maximum years,

$$15\ \frac{\text{millirad}}{\text{day}} \times 4 = 60\ \frac{\text{millirad}}{\text{day}} = 0.42\ \frac{\text{rad}}{\text{week}}$$

During solar minimum years,

$$20\ \frac{\text{millirad}}{\text{day}} \times 4 = 80\ \frac{\text{millirad}}{\text{day}} = 0.56\ \frac{\text{rad}}{\text{week}}$$

In the altitudes of interest, between 60,000 and 75,000 feet (18 to 23 km), this over-all physical ionization measures only in part the biological effect. The more heavily ionizing components that contribute to the ionization dosage and that have a higher RBE factor are, however, taken into account separately a second time later on in the two subsequent sections. Therefore, for comparison of a part of the biological effect with the guide lines, one can write roentgen or rem here.

The dose of 0.56 rad or 0.56 rem would be accumulated during a continuous stay of 1 week or 168 hours at an altitude of 23 km. Assuming a flight duty time for the crew of 80 hr/month (or 40 hr/month = 10 hr/week in these high altitudes), one has to divide the above dose rate by 16.8 to obtain the value

$$0.033\ \text{rem/week}$$

for the crew as this part of the biological dosage. This exposure level is one-third of the maximum permissible continuous dose rate for radiation workers, which is 0.1 rem/week or 5 rem/yr, as indicated in reference 10.

Contribution of Nuclear Stars

Van Allen introduced the biological effects of the heavy prongs (mainly low-energy protons and α-particles, in low Z-number material) of cosmic ray induced stars in the human body in terms of their equivalent of radium. The low-energy star components, being of short range and high specific ionization, resemble closely, in energy and ionizing characteristics, the α-particles and recoil nuclei from the radioactive decay of radium.

From the measured increase with altitude of nuclear stars per gram of nuclear emulsion per day (maximum of 600), from the chemical composition of biological tissue, and from data on the relative cross sections for star production in the various elements, a maximum expectation of about 850 nuclear stars per gram of biological material per day were deduced. If the ionization by radium is compared with the average ionization by the heavily ionizing products of stars, this number of stars per day is equivalent to a content of 0.35×10^{-7} gram or 0.035μC radium within the human body. Fast secondaries, mainly those originating in nuclear collisions in the roof material of the airplane, produce more stars within the human body; however, these are considered negligible in comparison with the stars produced at high altitudes by primaries and fast secondaries originating within the atmosphere. The latter were included as a safety margin in the above number (850).

The above-mentioned 0.035μC radium is one-third of the maximum permissible deposit (0.1μC) for radiation workers. Men would be exposed to this level of radiation if they remained continuously at an altitude of 23 km. Again this dosage must be divided by the factor 16.8 because the crew would stay at this altitude only 1/16.8 of the time. Thus, in addition to the physical ionization dosage, a maximum exposure level of 1/50 of the maximum permissible radium level for radiation workers would be obtained.

Heavy Primary Thin-Down Hits

In the previous estimate the biological effects of heavy primaries that come to rest by electronic collisions[3] within the human body are not taken into consideration. These heavy charged particles exhibit, especially on the end of their track, a specific ionization that is

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[3]Called "thin-down" hits because of the arrow shape of the terminal track.

higher, by a factor up to 20, than the maximum specific ionization of α-particle. (The specific ionization of an α-particle near the end of its path is $\approx 10^4 \frac{\text{ion pairs}}{\mu \text{ tissue}}$.) Furthermore, the terminal part of these long tracks of high ionization is surrounded by an aura of δ-rays[4] distributing the ionization in tissue over a width of about one cell diameter (≈10μ); high concentration prevails, of course, in the core only. The ionization track of a radium α-particle, in contrast, has a diameter of 0.5μ. The biological effect of broad long columns of ionization such as are exhibited by heavy primaries is considered to be more profound than the effect that corresponds to their contribution to the over-all ionization - which contribution is low, for example, at the top of the atmosphere, ≈5 percent - even if this ionization component is multiplied by a high RBE factor. The number of these thin-down hits per unit volume of the body is therefore a more adequate quantity on which to base their specific biological effect than is their contribution to the dose in rep or rad units.

The order of magnitude of the number of thin-down hits at very high altitudes is indicated by the results obtained during the Manhigh II balloon flight in August 1957 (ref. 15). During a stay of 15 hours at an altitude of over 90,000 feet (27.4 km) in latitudes greater than 55°, the number of calcium (Z = 20) up to iron (Z = 26) hits recorded in three 7.5- by 10-cm emulsion pellicles (thickness, 600μ), placed on the arms and the chest of the pilot were 3, 1, and 2. The number of lower Z-number terminal tracks per pellicle was in the order of 25. The total hit frequency was 2.6 thin-down hits/cm^3 emulsion/day. It should be mentioned that 1,170 stars/cm^3 emulsion/day were measured at the same flight. It has not been possible to detect biological effects during the years of observation of the pilot since the flight. This does not exclude, however, the possibility that effects might appear if the crew of a supersonic transport were exposed for periods of 480 hr/yr to this kind of low-level radiation. Of course, the thin-down hit frequency is substantially lower at 75,000 feet (23 km), the maximum altitude for supersonic transport, than at the altitude of the Manhigh II flight, as will be shown in the following discussion.

The number of thin-down hits/cm^3/day, the hit distribution inside targets, and the increase of the hit frequency with altitude and latitude have been thoroughly calculated by Schaefer (ref. 12, see further references therein) and also measured by Yagoda with emulsion stacks in

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[4]Tracks of expelled electrons in the Kev energy range.

numerous balloon flights at high latitudes. In figure 5 is shown the variation of thin-down hit frequency P (hits/cm^3 emulsion/day) with altitude for seasons of maximum and minimum sunspot activity, as derived by Yagoda (ref. 16, see further references therein) from these balloon measurements in northern latitudes. It can be noted that the hit frequency increases strongly above 80,000 feet (24.4 km, 28 g/cm^2). From 80,000 feet to the top of the atmosphere, the frequency increases by a factor of 6 during solar maximum activity and by a factor of as much as 20 during solar minimum activity. At 75,000 feet (22.8 km, 36 g/cm^2) the frequency is low and is approximately 0.6 hits/cm^3/day for solar maximum activity and 1.2 hits/cm^3/day for solar minimum activity. Furthermore, from the balloon flights of Commander Ross (discussed in ref. 16) at somewhat higher altitudes and from experimental data on collision cross sections of heavy nuclei, it is known that the heaviest primaries (Z > 20) cannot penetrate to such relatively low altitudes where only C, N, O, . . ., $_{20}$Ca are observed.

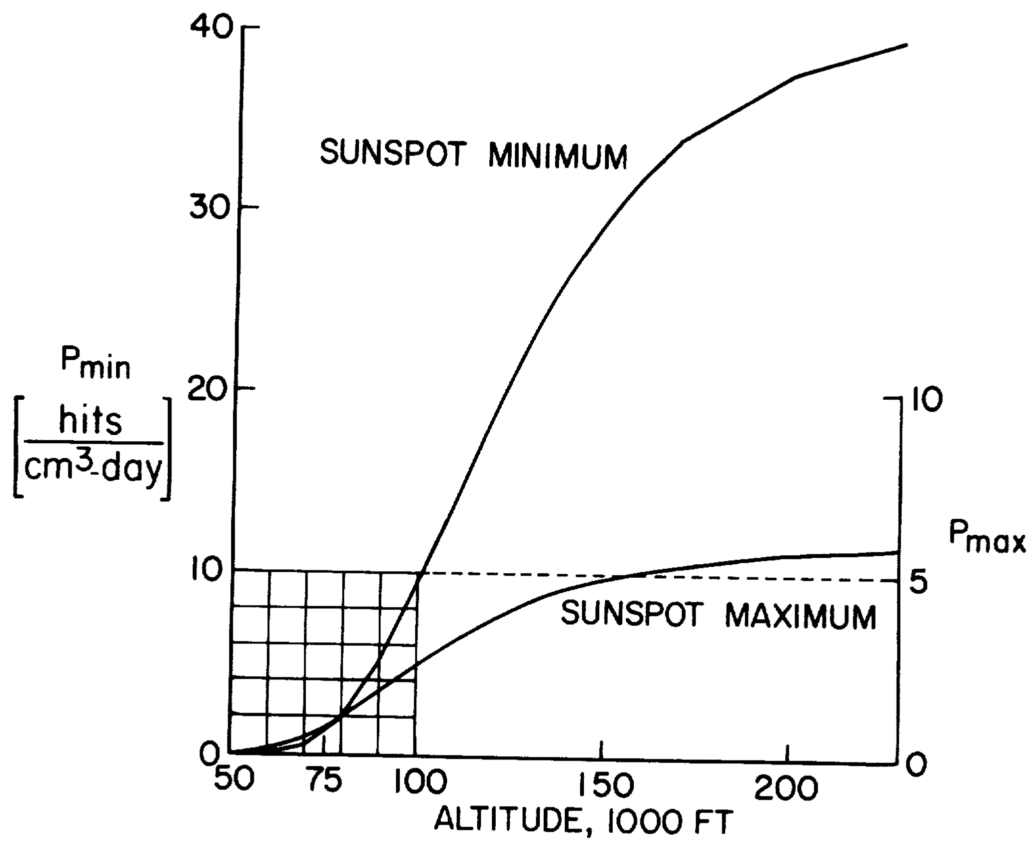

Figure 5.- Variation of thin-down intensity with altitude for seasons of maximum and minimum sunspot activity. (From ref. 16, H. Yagoda.)

From the result of Colonel Simons flight (Manhigh II) of about 1.6 hits/cm^3/15 hours above 27.4 km and from the hit frequency in figure 5 of ≈0.4/cm^3/15 hours in 23 km (75,000 feet) altitude it can be concluded that the crew is certainly safe at this altitude four times as long, that is, for 60 continuous hours, or $1\frac{1}{2}$ months duty time, during maximum solar activity years. Taking into account that the heaviest primaries are excluded in the lower altitude, this period may be doubled to give a duty time of 3 months. For longer periods there are not sufficient data nor flights of sufficient duration in high latitudes to provide a firm basis for evaluating radiation effects of this type and low level of irradiation, in spite of the penetrating and difficult theoretical and experimental work done by Schaefer (ref. 12), Yagoda (ref. 16), Tobias (refs. 17 and 18), and Haymaker (ref. 16); by balloon pioneers like Simons (ref. 15), Ross (ref. 16), and Chase and Post (ref. 16); and on a heavy-ion linear accelerator (HILAC) at Berkeley (Tobias et al., ref. 19) and a cyclotron at Brookhaven (Curtis, ref. 20). In order to clarify the biological effects of thin-down hits, it appears advisable to advance the experimental work for simulation on appropriate accelerators by extension to higher energies, and to provide a recoverable low-altitude polar satellite for exposing animals for periods of at least several weeks to this type of radiation. The next solar minimum year, 1965, appears especially favorable for such satellite experiments because the low-energy heavy-primary intensities will be high and no interferences will occur from aurora and flare radiations. It may be mentioned that simulation of heavy primaries by small deuteron beams (≈25μ diam.) had already significant results. (See Curtis, ref. 20.) Brain tissue was, against expectation, observed to be extremely resistant to this kind of needle radiation. In contrast to this result, wider beams of the same intensity lead to lesions, apparently because the blood capillaries were injured in a larger area and to such an extent that the blood supply to the nerve cells was suppressed. Relying on theoretical speculation for getting a rough survey of the total effect of thin-down hits distributed over the body on the more sensitive tissues, one may again use the previous model of radium α-particles, which reproduces, in this case, only the central most densely ionized part of the thin-down track and only up to 10^4 ion pairs/μ of this terminal track. This latter specific ionization seems to constitute a saturation value for the biological effect of thin tracks. Thus the core of the long heavy primary terminal track of low Z-number (C, N, O, . . ., $_{20}$Ca) is replaced by a corresponding number of radium α-particles in line, the aura of δ-rays being disregarded. About 500 Ra-α-particles (energy ≈4 Mev; range, 30μ; specific ionization, ≈10^4 ion pairs/μ tissue) in line would correspond to the terminal part of a $_{20}$Ca track (≈1.5-cm length, see ref. 21) where the specific ionization is highest and on the average $\gtrsim 10^4$ ion pairs/μ tissue.

Figure 5 shows about 1 thin-down hit/cm^3 emulsion/day, at an altitude of 75,000 feet (23 km), which by the present argument is considered to be equivalent to 500 α/cm^3/day. (The difference between hits/cm^3 tissue and hits/cm^3 emulsion is neglected here.) The maximum permissible radium content for radiation workers is 10^{-7} curie of radium per total body volume of 75×10^3 cm^3, corresponding to

$$\frac{3.7 \times 10^{10} \times 10^{-7}}{75 \times 10^3} \frac{\alpha\text{-particles}}{cm^3\text{-sec}} \quad \text{or} \quad 4.2 \times 10^3 \frac{\alpha}{cm^3\text{-day}}$$

The 500 α/cm^3/day is thus only one-eighth of the maximum permissible continuous internal exposure - exhibiting no clincial effects - for radiation workers. With 10 hours per week flight time of the crew at these altitudes, this number must further be divided by 16.8. Thus, $\approx 1/140$ of the maximum permissible exposure level for radiation workers is obtained.

Because of the questionable validity of the model of radium α-particles, shielding for the crew may be provided. About 30 g/cm^2 of low Z-number material (for example, water) would reduce the number of thin-down hits at an altitude of 75,000 feet by a further factor 4; thus the exposure level would be practically zero. The small hit frequency under such high shielding, in addition to the air shield of 36 g/cm^2, is not well known at the present time.

Cosmic Ray Showers

The question of the biological significance of cosmic ray showers originating within the atmosphere or condensed matter is treated by Schaefer in reference 12 and is only briefly summarized herein according to these considerations and the work of Rossi (ref. 4). Extensive air showers (EAS) are electronic photonic cascades associated with large nuclear cascades, which originate in one single collision of an extreme energetic primary with an air atom. Electronic photonic showers have been encountered down to sea level and even below sea level. Dense shower events, are, however, extremely rare. The denser a shower, the less frequently it will occur. According to an empirical and approximate formula stated by Singer (ref. 22), the following numbers at sea level in northern latitudes are obtained:

Flux density, particles/m^2	Frequency
>10	20 events/hr
>100	1 event/hr
>1000	1 event/day

The characteristic altitude profile of shower frequency should be furthermore mentioned. The frequency of EAS is highest at an altitude of about 22,000 feet (6.7 km), which is in the altitude range of flights today. The shower frequency decreases with higher altitudes and is, for example, lower than this maximum by about a factor 10 at 50,000 feet and is about the same as at sea level at 75,000 feet. Since the primary flux of the galactic cosmic rays in free space is about 25,000 particles/m^2/sec, the biological effect of cosmic rays, which is in itself low, cannot be significantly increased by air showers, especially because these showers consist of lightly ionizing particles or quanta.

Nuclear cascade particles produce photonic electronic showers not only in air but also in condensed and especially high atomic material, such as a metallic cover. These local extensive showers are observed to increase in frequency under increasing material thicknesses up to a maximum frequency and then to decrease. A significant increase, however, is observed only beneath thicknesses of several centimeters of high-atomic-number material such as lead. The thickness of the roof of an aircraft fuselage is too low to increase the number of extensive showers significantly. The density of such rare local showers is higher than the density of air showers; nevertheless, the tissue ionization dosage would not surpass the millirad level, even for extreme events, that may occur once a year. Also, dense meson cones, which are produced in rare nuclear collisions involving energies of the order 10^{11} to 10^{12} ev, should not release cellular doses which are comparable with the cellular ionization dosage produced by the terminal sections of heavy nuclei.

Survey on the Galactic Cosmic Ray Doses in Supersonic Transport

Table I summarizes the exposure rates for the crew produced by different components of galactic cosmic rays insofar as these components appear significant with respect to biological effects. A duty time of 40 hr/month at an altitude of 23 km is assumed.

TABLE I

GALACTIC COSMIC RAYS

Upper Limits of Exposure for Crew

[40 hr/month duty at 75,000 ft (23 km) altitude, >50° magnetic latitude, solar minimum years]

Components	Level of exposure for -		Maximum permissible level[a]	Fraction of maximum permissible level
	Continuous stay	10 hr/week duty at 75,000 ft		
Over-all ionization	0.56 rem/week	0.033 rem/week	0.1 rem/week	<1/3 = 33 percent
Nuclear bursts	0.035 μC	0.002 μC	0.1 μC	<1/50 = 2 percent
Heavy primary thin-down hits	≈1/cm³/day	≈0.4/cm³/week or per 10 flights	?	? ≈ 7 percent (safety factor 10)
Core only	=500 α/cm³/day	30 α/cm³/day	0.1 μC = 4.2 × 10³ α/cm³/day	1/140 = 0.7 percent

[a]Maximum permissible level for continuous occupational exposure (50 years duty).

Maximum dosage for solar minimum activity years:
Crew: 0.42 × Maximum permissible occupational exposure
Passengers: 0.042 × Maximum permissible exposure at one flight per week

These dose rates are considered as upper limits and would be received during solar minimum years, when the galactic cosmic rays are highest in intensity. On the basis of the introduced simplifications, it appears that the contribution of heavier ionizing particles is low in comparison with the over-all ionization dosage, if both are expressed in fractions of the maximum permissible radium allowance or maximum permissible ionization, respectively.

The galactic cosmic ray exposure rates for solar maximum years are summarized together with solar proton dose rates in tables III and IV in the last section of this report.

SOLAR FLARE PROTONS

Characteristics of Major Solar Flare Proton Events

The energetic proton streams that are associated with major solar flares on the sun encounter the earth sometimes with an intensity which is several orders of magnitude higher than that of galactic cosmic rays. In some cases, they are able to penetrate the atmosphere, even down to sea level, as has been observed with cosmic-ray monitors since 1942. In these relatively rare high-energy events, the particles have energies from 30 Mev to 20 Bev. A second class of lower energy flare proton showers, appreciably more frequent than high-energy events, has been brought to light since 1957 by combination of balloon, ionospheric, satellite, and space-probe measurements. Their particles have energies from 30 Mev to 400 Mev in low-energy events ("low energy" in comparison with the average energy of galactic cosmic rays) and from 1 Bev to 2 Bev in medium-energy events.

As an indication of the penetrating power of such high energetic protons, it may be recalled that protons with an energy of 300 Mev have a range of about 50 cm in water or 57 g/cm^2 in air, if they come to rest by electronic collisions without undergoing nuclear collisions. Protons with an energy of 1 Bev have a nominal range of about 3 meters in water. Actually these high-energy protons would mostly collide with the atomic nuclei of an absorber of 300 g/cm^2 thickness and produce secondaries before they reach the end of their range in electronic collisions. It is evident that these solar particles penetrate to supersonic-flight altitudes and must be taken into account for an estimate of exposure rates in supersonic transports.

The flare proton fluxes vary within wide limits - by about six orders of magnitude - from cosmic ray background fluxes of a few particles/cm^2-sec, corresponding to a dose rate of 0.5 rad/week in free space, up to possibly 10^6 protons/cm^2-sec early in a large event. Such high flux values would correspond to a dose rate of thousands of rad/hr behind a small amount of shielding in free space. The extreme events are, of course, rare; most flare proton beams would not produce a significant exposure level in an aircraft at 36 g/cm^2 atmospheric depth or 23 km altitude. In order to assess the upper limits of exposure, the more concise data on frequency, duration, spectra, and other characteristics of extreme events will be briefly summarized. These data are far from complete for a definite assessment of the radiation exposure in supersonic transports.

Figure 6 shows the frequency of high-energy events continuously monitored since 1938 and the sunspot and flare activity during the last three solar cycles. The events are indicated by vertical bars. About one or two high-energy events occurred every 4 or 5 years. Two recent medium-energy events should be added; they were the most intense observed. They occurred on November 12 and 15, 1960, during the decreasing phase of the present solar cycle.

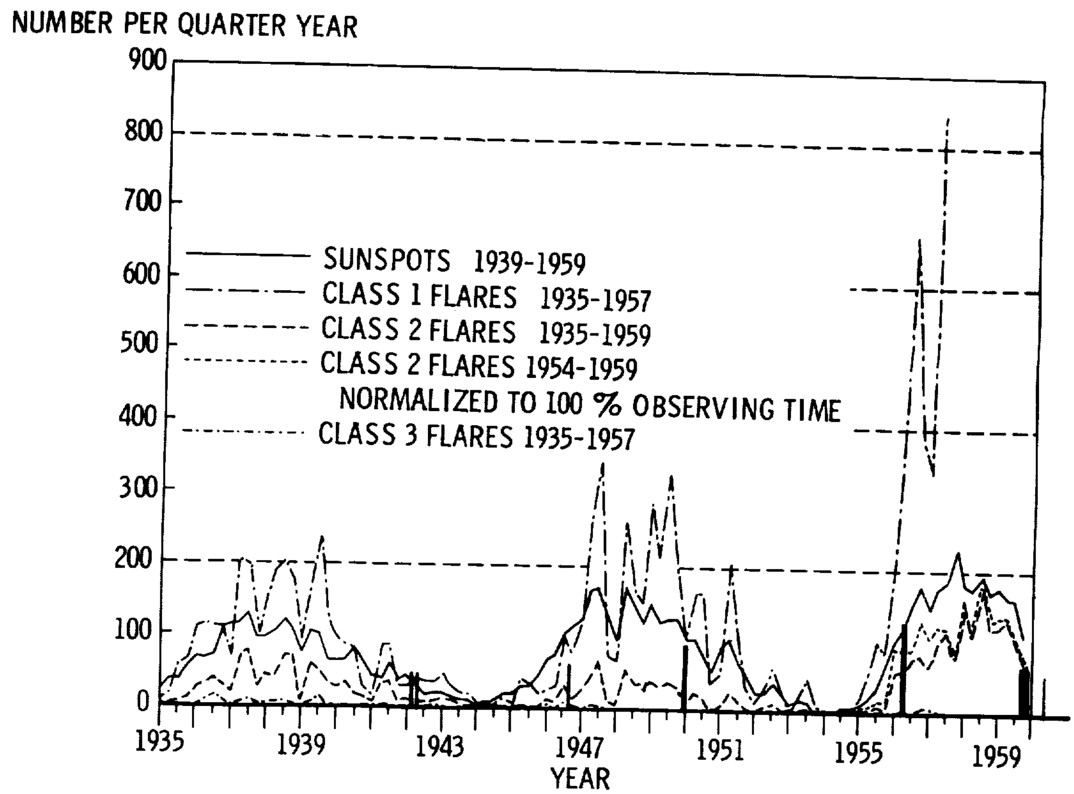

Figure 6.- Frequencies of sunspots and flares in the last solar periods and high-energy proton events. (Courtesy J. W. Evans, Sacramento Peak Observatory, New Mexico.)

Figure 7 shows also the frequency of low- and medium-energy events as derived from measurements of cosmic radio noise absorption and radio waves scattering in the polar regions. About 5 to 13 events or event groups per year, mostly of low intensity, occurred during the high-activity years (refs. 7 and 23). Extreme-flux low- or medium-energy events occurred at a rate of only 2 to 4 per year during the activity years of the present solar cycle. The duration of the maximum phase of these flare proton events varies considerably in different cases. In the most intense high-energy event yet observed after the flare of February 23, 1956, the time of intensity rise of

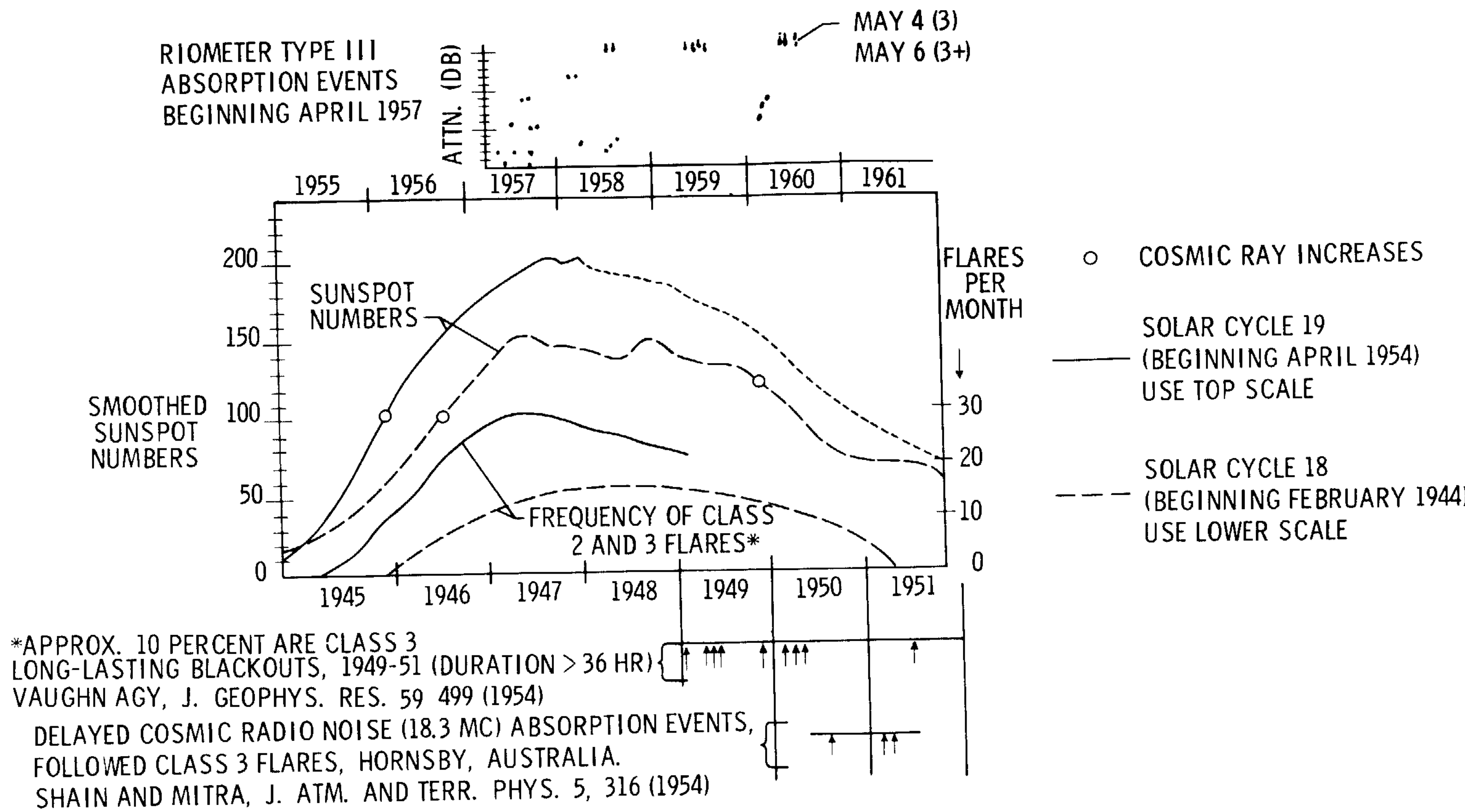

Figure 7.- Solar activity and radioabsorption events in the solar activity period.
(Courtesy L. R. Davis, Goddard Space Flight Center.)

high-energy particles and subsequent decay to 50-percent intensity was of the order of 1 hour and was followed by a slow decrease in the later phase of the event (≈1 day). In the cases of the extreme-flux low-energy events of May and July 1959 and also of November 12, 1960, this maximum period was of the order of 1 day. Very low intensities were still observed after $10\frac{1}{2}$ days in the event after the flare of July 16, 1959. The radiation is observed arriving from all directions in the geomagnetic polar regions, similar to the galactic cosmic radiation, although this solar cosmic radiation is clearly associated with flares on the sun. The omnidirectionality and approximate isotropy is established within the first 10 to 20 minutes after onset of the proton influx. This isotropy, together with the fact that the spectral intensity falls off steeply at particle energies above 1 Bev, has the consequence that the main intensity of protons arrives in the polar regions and is cut off in most cases by the magnetic field of the earth for magnetic latitudes lower than 60°. During magnetic storms when the geomagnetic field is depressed in high latitudes, the particles of low- and medium-energy showers are also observed with significant intensity in lower latitudes, for example, above Minneapolis (55° geomagnetic latitude) or even at 50° magnetic latitude. One high-energy event has been observed thus far, that of February 23, 1956, which produced a small increase of meson intensity in mountain altitude even near the equator. This increase indicates high-energy protons (>10 Bev) of low intensity arriving on top of the atmosphere above the equator. Persisting intense proton influx is generally limited to regions above 50° magnetic latitude. This lower northern limit crosses the west coast between San Francisco and Vancouver, the east coast (near Philadelphia), and then Berlin, Moscow, the southern Siberian tundra, northern Kamchatka, and the midst of the Aleutian islands. (See fig. 11.)

Flare Proton Dose Rates

In order to estimate the dose rates that might occur during a flare proton event, first the experimental results obtained with ionization chambers in balloon ascents during such events is considered. In figure 8 (from ref. 7) is shown the increase of ionization with increasing altitude of the balloon at Minneapolis (55° magnetic latitude) 31 hours after the flare of July 14, 1959, that is during the later decay phase of a very-high-flux low-energy event, when the particles had full access to this low latitude because of a magnetic storm. At an atmospheric depth of about 7 g/cm^2 (altitude 33.5 km, or 110,000 feet), the dose rate was measured as 0.15 rad/hr. At an atmospheric depth of 36 g/cm^2 (23 km or 75,000 feet), the dose rate was only in the order of 1.5 millirad/hr. At the maximum phase the dose rate may have been tenfold higher, or 15 millirad/hr. For two round trips, which could take place during such an event, the crew would be exposed for 4 hours

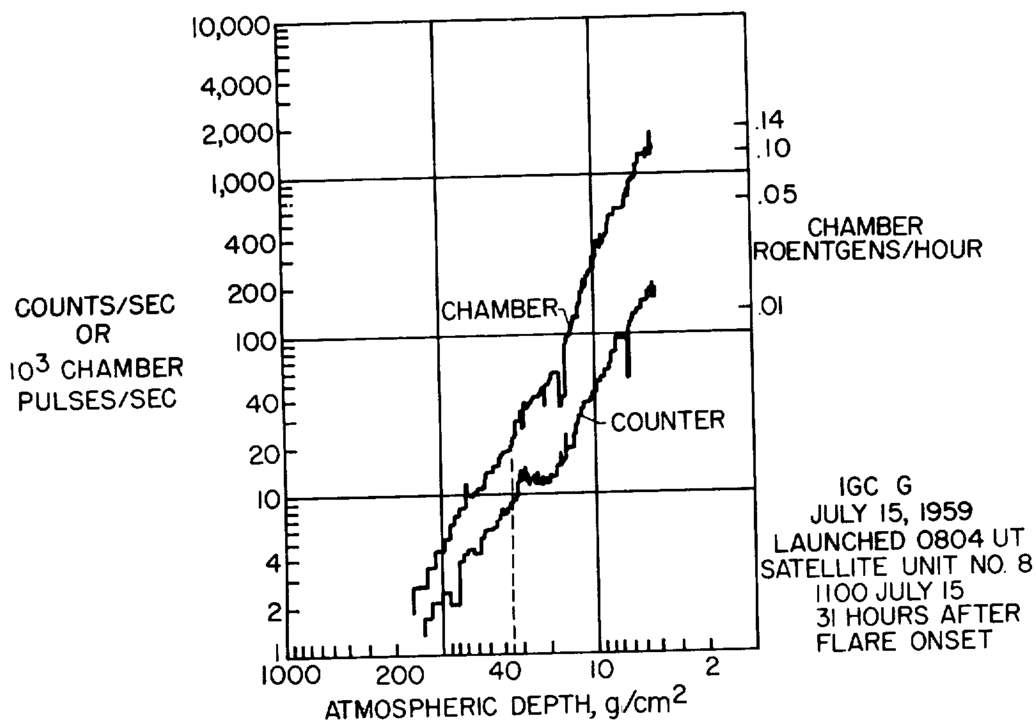

Figure 8.- Altitude dependence during a period of high intensity. This flight ascended between 0800 and 1100 universal time on July 15, 1959. (From ref. 7, J. R. Winckler.)

(1 hour each way). For four such events per year, the total exposure would therefore become 0.24 rad/yr. Since the maximum permissible dose rate is 5 rem/yr, there remains a safety factor of 20 to allow for the higher values of RBE of secondaries and for error in estimating the intensity. (See also table II.) Because the event of July 14, 1959, was one of the most intense low-energy events, it seems justifiable to consider the low-energy events as a minor hazard, even those of extreme intensity, of which two to four occurred per year and only near solar maximum activity years.

In the cases of medium- and high-energy events a more cautious attitude must be observed because of the rapidly increasing range of more energetic particles. As an example, the high-energy event of February 23, 1956, may be considered. Although no direct ionization measurements were made within the high atmosphere during the maximum phase of this event, the large amount of data accumulated on a world-wide basis during this event allows estimation of a relatively trust-worthy spectrum and its variation with time, or at least of upper limits of the fluxes in these spectra. For the calculation of the ionization exposure in rad/hr or rem/hr at different atmospheric depths, the intensity as a function of particle energy must be known. Integral spectra of the event of February 23, 1956, are shown in figure 9, as derived and extrapolated by Winckler (ref. 7) and Bailey (ref. 24) on the basis of measurements by Meyer, Parker, and Simpson (ref. 25), Van Allen and Winckler (ref. 26), Winckler (ref. 27), and Bailey.

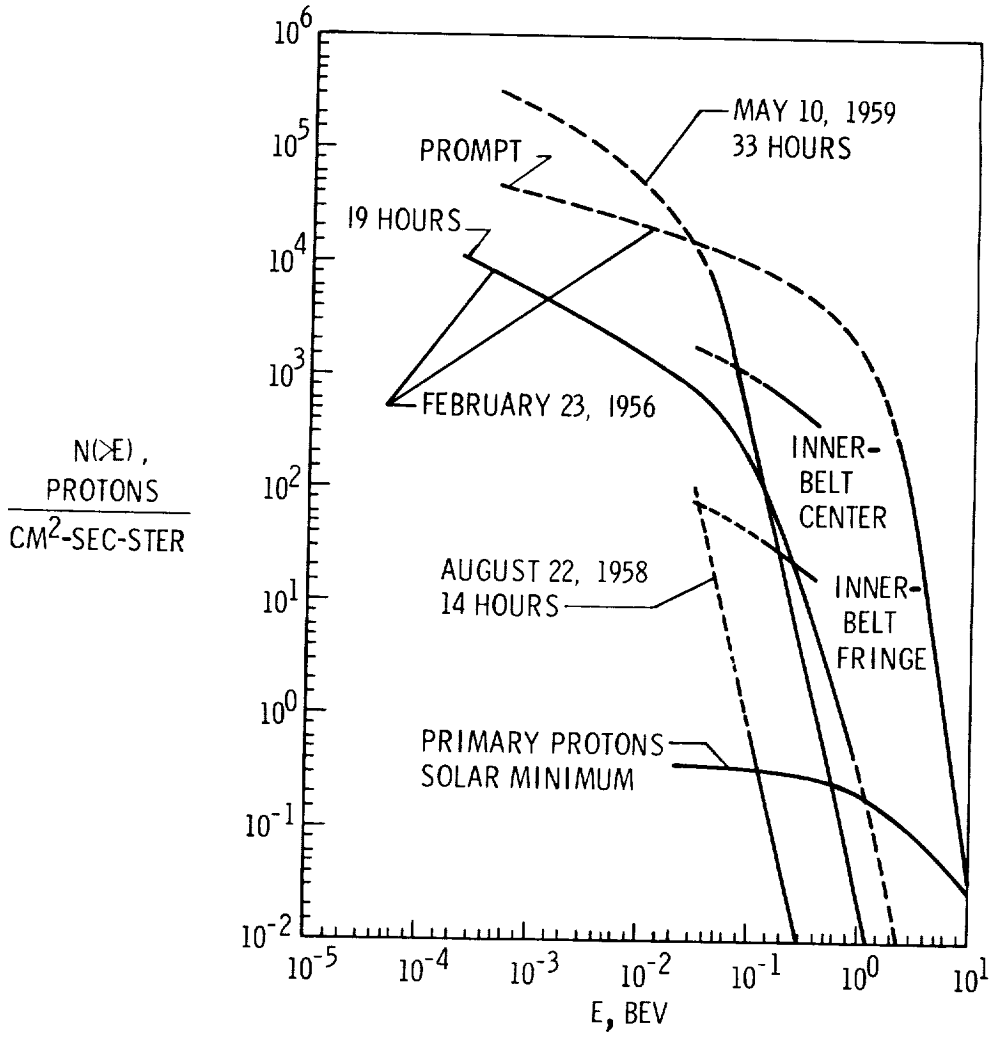

Figure 9.- Integral energy spectra of solar-flare cosmic rays, inner-belt protons, and galactic primary protons. (The spectra are plotted on an energy scale from the integral rigidity spectra given by Winckler, ref. 7; Anderson, Arnoldy, Hoffman, Peterson, and Winckler, ref. 28; and by Freden and White, ref. 29.)

For comparison, spectra of low-energy events (refs. 7, 28, and 29), of protons in the inner Van Allen belt, and of galactic cosmic protons are also shown in figure 9. (For further references and discussion, see ref. 30.) These spectra allow the calculation of the dose rate behind different thicknesses of spherical or flat shields for the particular time at which the spectrum existed. The result of these calculations, assuming only electronic collisions and neglecting nuclear collisions and their secondaries, for spherical water shields are shown in figure 10.

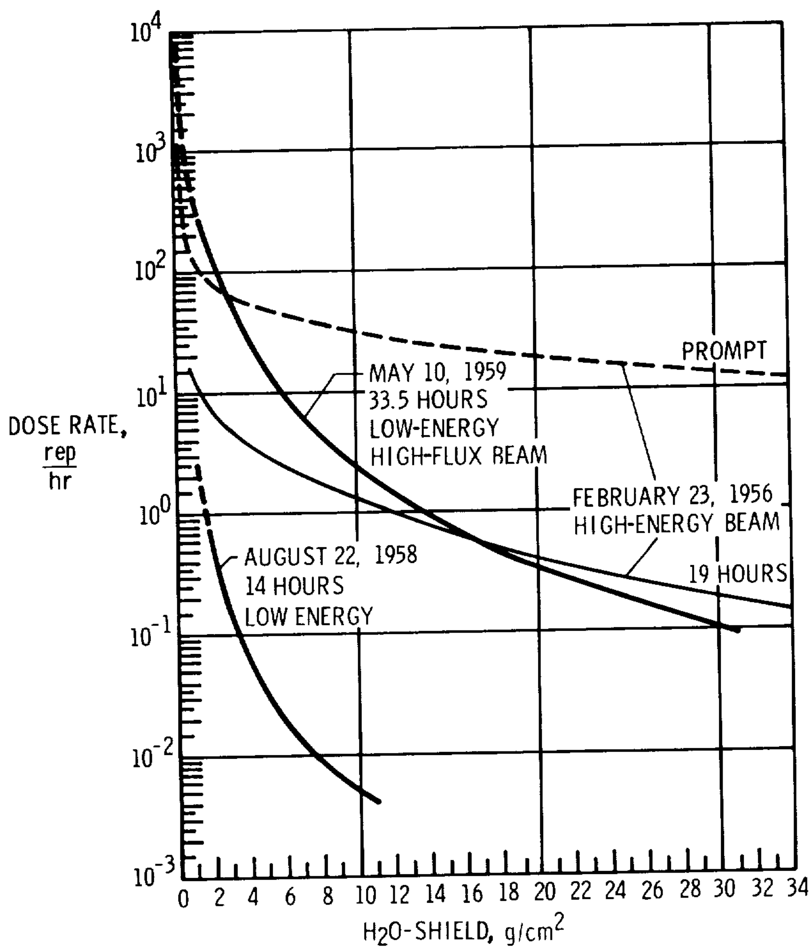

Figure 10.- Proton dose rates in the center of spherical shields of water of different thicknesses derived from the spectra. (From ref. 30.)

As expected in the low-energy events (May 10, 1959 and August 22, 1958), the dose rate decreases very rapidly with increasing shield thickness, but the decrease is slow in the high-energy event of February 1956, especially for the prompt spectrum, when the intensity was at its peak. Inside a spherical shield with a thickness of 25 g/cm^2, the dose rate of about 18 rad/hr is obtained; inside a shield with a thickness of 36 g/cm^2, it would be about 11 rad/hr, or 5.5 rad/hr above the earth's atmosphere near the poles where the radiation arrives only from a solid angle of 2π. Of course, below a flat shielding layer of 36 g/cm^2 of air, that is, in flight at an altitude of 23 km, the dose rate would be lower than inside a spherical shield because a larger proportion of the particles arrive at oblique angles and are more attenuated along the longer paths. With decreasing altitude, the direction of the residual radiation that penetrates to the target is limited to smaller solid angles in the vertical direction.

The following table lists the approximate dose rates at different altitudes during the early phase of the February 1956 high-energy event:

Altitude in -		Air layer, g/cm^2	Upper limits of dose rate, rad/hr (a)
km	ft		
37.8	124,000	4	35
22.8	75,000	36	4
15.2	50,000	100	.8
12.2	40,000	188	.06

[a]The dose rates are obtained by a Gross transformation from figure 10.

Because of the high penetration power of this hard radiation, the value of 4 rad/hr at 22.8 km or 75,000 feet is only slightly less than the dose rate inside a spherical shield with a thickness of 36 g/cm^2. (The value of 11 rad/hr in fig. 10 has to be divided by 2, because near the earth the radiation arrives only from a solid angle 2π.) The dose rates presented for the high-energy event of February 1956 are furthermore preliminary estimates since no secondaries are taken into account. The biological dose rate in rem/hr may be higher because of the higher biological effect of secondaries from nuclear collisions, especially low-energy nuclei and neutrons.

It may be mentioned, on the other hand, that the basic prompt spectrum of the high-energy event derived by Winckler is, in part, extrapolated and is considered as a highly conservative upper limit.

With reference to medium-energy events, most data are available on the events of November 12 and 15, 1960. The November 12 event seems to have been the most intense medium-energy event observed so far. The event after the flare of July 16, 1959, might have been comparable in intensity in the lower energy range - the maximum intensity phase of this event could not be observed - its duration was longer. The increase of neutrons at sea level in high latitudes was, however, less than the increase observed on November 12, 1960, and indicated lower flux in the hundreds of Mev range and Bev range, the latter being of particular significance in supersonic-flight altitudes.

During the event of November 12, 1960, the dose rate, in free space inside 36 g/cm^2 water shield, calculated as before on the basis of the spectrum measured in the hours of maximum neutron intensity, would have been lower by a factor of at least 4 (more probably by a factor 10) than in the previously treated February 1956 event. Conservatively a maximum dose rate of 1 rad/hr (safety factor of 2 to 3) in an altitude of 23 km above the poles is assumed in table II for extremely intense medium-energy events, which are observed to occur with a maximum frequency of 2 per year during solar activity years.

Upper Limits of Flare Proton Doses in Supersonic Transport Flights

The previous conservative estimates of doses received by crew and passengers on polar routes if no precautions are taken (such as, for example, descent to lower flight altitudes during extreme medium- and high-energy events) are summarized in table II.

One flight, as it is visualized today, would last about 2 hours. The cruising time in high altitudes up to 23 km would be about 1 hour per flight. A flight duty time of 80 hr/month is assumed for the crew or 40 hr/month in high altitudes.

The primary protons themselves that penetrate to supersonic-flight altitudes contain only a very small fraction of low-energy particles; hence, their RBE factor can be assumed as being 1.

In the last column of table II, the fraction is calculated by replacing the rad units in the second column by rem; hence, no account is made of the higher biological effectiveness of secondaries produced in nuclear collisions. This is considered as justified because the rad dose rates in the second column include high safety margins. Thus, the average number of extreme proton events per year are assumed to be the maximum number observed during any year of the last solar cycle. The

TABLE II

SOLAR COSMIC RAYS

Upper Limits of Exposure for Crew Without Precautions

[40 hr/month duty at 75,000 ft (22.8 km, 36 g/cm^2 of air) altitude, >50° magnetic latitude (polar regions), solar activity years]

Event	Preliminary estimate of dosage[a] for -	Maximum permissible level[b]	Fraction of maximum permissible level
Low energy - 2/yr to 4/yr Extreme flux 20 hr	Two round trips (4 hr) per event; dose rate, 15 millirad/hr: $\frac{4}{yr} \times 4\ hr \times 15\ \frac{millirad}{hr} = 0.24\ \frac{rad}{yr}$	5 rem/yr	$\frac{1}{20}$ = 5 percent
Medium energy - 2/yr Extreme flux 20 hr	Two round trips (4 hr) per event; dose rate, 1 rad/hr: $\frac{2}{yr} \times 4\ hr \times 1\ \frac{rad}{hr} = 8\ \frac{rad}{yr}$	5 rem/yr	$\frac{8}{5}$ = 160 percent
or			
High energy - Maximum: 2 in short succession every 4 yr High flux 1 hr	One trip (1 hr) per event; dose rate, 4 rad/hr: $\frac{2}{yr} \times 1\ hr \times 4\ \frac{rad}{hr} = 8\ \frac{rad}{yr}$	5 rem/yr	$\frac{8}{5}$ = 160 percent

[a]The rad values contain a high safety factor.
[b]Maximum permissible level for continuous occupational exposure (50 years duty).

Maximum dosage for solar activity years:
Crew: 1.6 × Maximum permissible occupational exposure
Passengers: 0 to 0.8 × Maximum permissible (0.8 maximum, if passing two medium- or one high-energy event)

last solar cycle was moreover the most sunspot-active cycle during this century. The average occurrence of extreme events would be lower by a factor of 2 to 4. Furthermore, the maximum dose rate of 4 rad/hr for the outstanding February 1956 high-energy event is derived from a conservatively extrapolated spectrum, and this dose rate is assumed to prevail during the whole hour of flight in high altitudes. In reality the flux of high-energy particles decreased within the first hour after the peak by a factor 2. Preliminary estimates of the upper limit of the contribution of secondaries result only in a rem dose rate higher, by a factor 2, than the rad dose rate obtained if secondaries are disregarded.

Protection Measures and Predictability of Major Events

Considering the conservative assumptions on which the values in table II are based, it appears improbable that the upper limits of doses given in this table will be reached even during the years of highest flare activity within the solar cycle. Some measures to reduce the dosage might nonetheless be mentioned.

The addition of a shield of 50 g/cm^2 of low Z-number material over the entire occupied compartment (for example, by arrangement of fuel tanks over the compartment) would certainly diminish the dose in polar regions substantially below 5 rem during the most active year. It seems more practical, however, to maintain a sufficiently low flight altitude during such rare events; thereby, the more effective natural shielding of a sufficiently thick air layer is used instead of artificial shielding. If the supersonic aircraft is provided with the capability of reaching its destination at flight altitudes below 50,000 feet (15.2 km) during much of its flight, it would be possible to avoid rerouting of the airplane and intermediate landings.

Some remarks may be added on the predictability of these high-flux medium- and high-energy events. At the present time it is not possible to predict the imminence of intense high- and medium-energy events for more than 10 to 15 minutes in advance of the onset of the high-energy proton influx. This period of 10 to 15 minutes is based on the observation that a strong radio-noise storm precedes the proton influx by at least 15 minutes and that such extreme energy events as those that are considered here - also extreme-flux low-energy events - are observed only after flares of importance 3+. These occurred at a maximum frequency of 4 per year in the last solar cycle, and can be identified by optical observation at least 10 minutes before onset of the proton influx. The increase of the high-energy-proton intensity to its peak took 20 to 30 minutes more. Thus the pilot could be warned 10 minutes before onset of the proton influx and has 20 minutes time for descent, if he observes increasing radiation on his own radiation monitors. If a proton event is in progress before the flight is initiated or reaches the polar regions, there is the possibility that the airplane may be rerouted so that the flight path stays under the earth's magnetic shield.

The research to predict, for some hours in advance, the imminence of 3+ flares or even of major energetic events from, for instance, characteristic features of activity regions on the sun (correlations are found between the magnetic type of active regions and major flares) and from pre-event effects measured near the earth and in interplanetary space, is still in the beginning stage. Reliable forecast methods for such longer periods would give the flight planner more time.

As a further measure of protection, the crews on polar routes after one event may be exchanged with the crews on equatorial routes. This measure is considered in more detail in the next section. Because of the rare occurrence of such events, it seems that they will become at infrequent times another environmental factor for aircraft flight planning similar to bad storms, but in no way, of course, constituting a comparable potential hazard.

SUMMARY ON UPPER LIMITS OF TOTAL RADIATION EXPOSURE AND CONCLUDING REMARKS

Before summing up the upper limits of total exposure, the previously discussed facts on space and time distribution of cosmic radiations may be recalled first. Both the galactic cosmic rays with their secondaries and the solar cosmic rays are limited in their main flux to geomagnetic latitudes above 50°, that is, to the northern and southern regions beyond these latitudes toward the poles. The ionization produced by galactic cosmic rays in the high atmosphere decreases sharply toward lower latitudes or the equatorial region by a factor 1/15 or 1/30. Ionization due to solar cosmic rays decreases even in a larger degree below this latitude. It may be recalled, furthermore, that during the 1 to 2 years of minimum sunspot activity the ionization produced by galactic cosmic rays within the atmosphere is higher than during the 9 years of higher solar activity and that during solar minimum years no major flare events are observed.

Table III summarizes the upper limits of radiation exposure of the crew on polar routes produced by galactic cosmic rays and solar cosmic rays if no precautions are taken. The effect of heavy primaries, and especially of the terminal part of their tracks, is understated by using the comparison with the indicated number of α-particles and are more adequately taken into account by multiplying the radium equivalent by an estimated factor 10. Their effects are not definitely known at the present time. However, consideration of the small number of hits per cubic centimeter of tissue per day and of the short flight duration experienced by the flight personnel and especially the passengers suggests that this effect may be insignificant.

From table III, at unrestricted flights of the same crew on polar routes for 40 hr/month duty time at an altitude of 23 km, the following conservative upper limits (within the mentioned limitations) of total exposure levels are obtained:

During solar activity years,

≈200 percent of the maximum permissible level for continuous exposure

During solar minimum years,

≈42 percent of this maximum permissible level

TABLE III

SUMMARY OF UPPER LIMITS OF TOTAL EXPOSURE FOR CREW WITHOUT PRECAUTIONS

[Polar routes, 40 hr/month duty at 75,000 ft (23 km) altitude]

Components or event	Maximum permissible level	Solar minimum years			Solar activity years		
		Level for continuous stay	Level for 10 hr/week duty	Fraction of maximum permissible level[a]	Level for continuous stay	Level for 10 hr/week duty	Fraction of maximum permissible level[a]
Galactic cosmic rays							
Over-all ionization	$0.1 \frac{rem}{week}$ $= 5 \frac{rem}{yr}$	$<0.56 \frac{rem}{week}$	$<0.033 \frac{rem}{week}$ $= 1.67 \frac{rem}{yr}$	$<\frac{1}{3}$ = 33 percent	$<0.42 \frac{rem}{week}$	$<0.024 \frac{rem}{week}$ $= 1.25 \frac{rem}{yr}$	$<\frac{1}{4}$ = 25 percent
Nuclear bursts	0.1 μC	<0.035 μC	<0.002 μC	$<\frac{1}{50}$ = 2 percent	(Values would be smaller than given for solar minimum years)		$<\frac{1}{50}$ = 2 percent
Heavy primary thin-down hits	?	$\approx 1/cm^3/day$	$\approx 0.4/cm^3/week$	? (7 percent)			<7 percent
Core only	0.1 μC	$500\ \alpha/cm^3/day$ = 0.012 μC	$30\ \alpha/cm^3/day$ = 0.007 μC	$\frac{1}{140}$ = 0.7 percent			$<\frac{1}{140}$ = 0.7 percent
Total per year:				42 percent			35 percent
Solar cosmic rays							
Low-energy events - 2/yr to 4/yr 20 hr	$5 \frac{rem}{yr}$	0	0	0	For two round trips (4 hr) per event with dose rate of 15 millirad/hr: <0.24 rad/yr		$<\frac{1}{20}$ = 5 percent
Medium-energy events - 2/yr 20 hr	$5 \frac{rem}{yr}$				For two round trips (4 hr) per event with dose rate of 1 rad/hr: <8 rad/yr		$<\frac{8}{5}$ = 160 percent
or High-energy events - Maximum: 2/yr every 4 yr 1 hr	$5 \frac{rem}{yr}$				For one trip (1 hr) per event with dose rate of 4 rad/hr: <8 rad/yr		
Total per year:							165 percent
Total per year (both galactic and solar cosmic rays):				42 percent			200 percent

[a]Maximum permissible level for continuous occupational exposure (50 years duty).

It should be understood that the maximum permissible occupational levels for continuous exposure as stated by the International Commission for Radiation Protection or by the Federal Radiation Council (5 rem/yr or 0.1μC) are based on a continuous 50 years of occupational life. It may be emphasized that these maximum dosages for radiation workers imply no observable or discernible effects and are stated with due consideration of genetic effects. For shorter periods, a higher exposure by a factor 2 or more is allowed if, as a whole, the 50-year dose is not surpassed. Indeed, since the occupational career of the crew is generally below 50 years and since the presented data are conservative upper limits, the maximum permissible exposure would hardly be reached during professional duty. For passengers, in the light of present knowledge, the small ionization doses as well as the heavy primaries carry an even lower probability of somatic and genetic injuries.

It is nonetheless desirable to hold any radiation exposure in excess of natural and medical exposure (medical exposure can reach 15 rad in 5 minutes during fluoroscopy for a part of the patient's body) as low as possible. Hence, protection measures are mentioned that would substantially reduce the exposure rates. Figure 11 shows the northern line of 50° magnetic latitude beyond which galactic and solar cosmic radiation should be taken into account. As seen from this figure, about 50 percent of the traffic flow is, at present, concentrated above 50° magnetic latitude and 50 percent below this latitude. If the same flow pattern should continue in supersonic transports, it would be possible to reduce the higher radiation exposure of the crews on northern routes, if necessary, by exchange with crews on equatorial routes after corresponding time intervals. By this measure, the exposure level from galactic cosmic rays can be cut to one-half or to about 20 percent of the maximum permissible level. A second but more important protection measure is to descend down to an altitude of about 45,000 feet during intense high- and medium-energy solar proton events and to continue the flight in this lower altitude. This measure should not seriously impair the economy of supersonic transports, since such extreme events occurred only twice during few of the solar activity years.

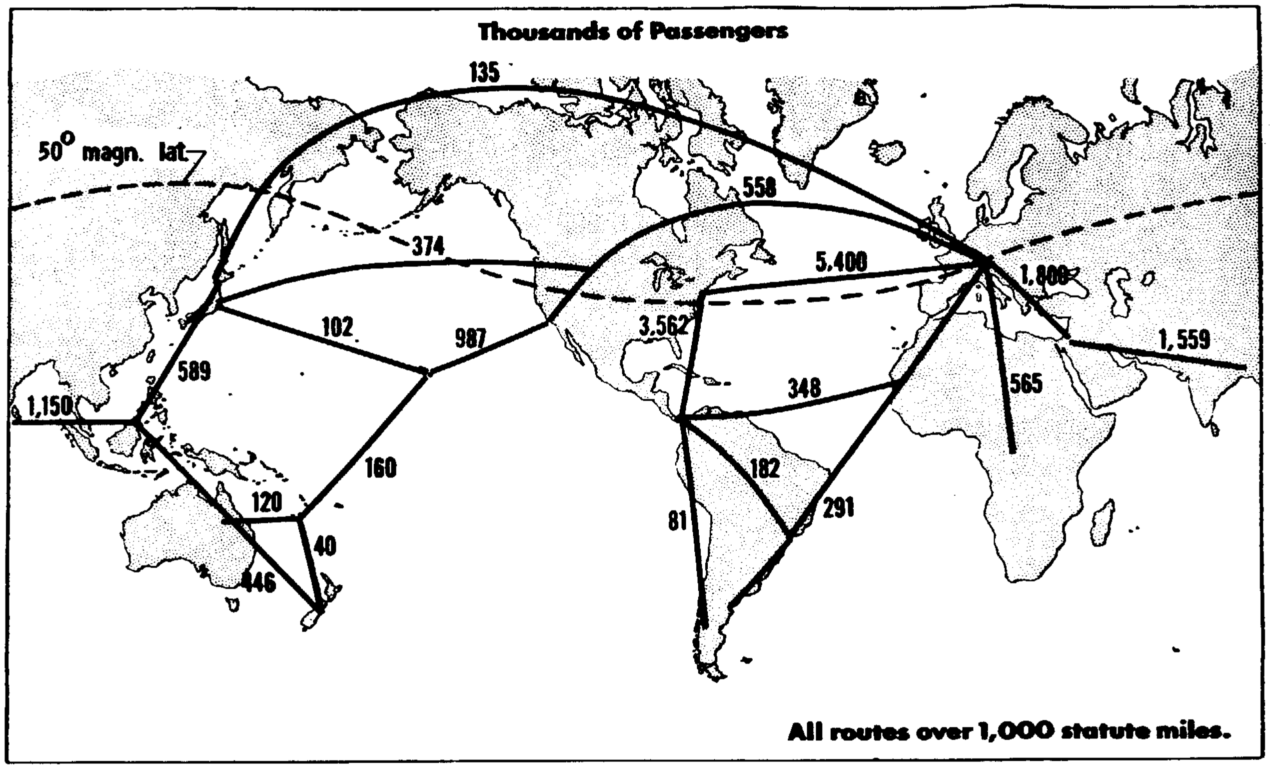

Figure 11.- World airline traffic flow. (Courtesy of Convair.)

TABLE IV

UPPER LIMITS OF EXPOSURE
(POLAR ROUTES)

[Precautions: (1) Exchange of the crew after 6 months/yr with equatorial crew
(2) Flight at altitude of 45,000 ft during high- and medium-energy solar events]

Components or event	Solar minimum years: Level for 10 $\frac{hr}{week}$ duty at 75,000 ft	Solar minimum years: Fraction of maximum permissible level[a]	Solar activity years: Level for 10 $\frac{hr}{week}$ duty at 75,000 ft	Solar activity years: Fraction of maximum permissible level[a]
Galactic cosmic rays: Over-all ionization	$0.017 \frac{rem}{week} = 0.88 \frac{rem}{yr}$	$\frac{1}{5.7}$ = 18 percent	$0.012 \frac{rem}{week} = 0.625 \frac{rem}{yr}$	$<\frac{1}{8}$ = 12.5 percent
Nuclear bursts Thin-down hits	(See table III)	$\approx\frac{1}{20}$ = 5 percent	(See table III)	$\approx\frac{1}{20}$ = 5 percent
Total per year:		23 percent		17.5 percent
Solar cosmic rays: 1 to 2 high-energy events per year every 4 yrs 1 hr	0	0	For one trip (1 hr) per event with dose rate of 0.2 $\frac{rad}{hr}$ and altitude of 45,000 ft: 0.4 $\frac{rad}{yr}$	$\frac{1}{12.5}$ = 8 percent
Total per year:				8 percent
Total per year (both galactic and solar cosmic rays):		23 percent		25 percent

[a]Maximum permissible level for continuous occupational exposure (50 years duty).

Upper limits of radiation exposure for the crew with the previously mentioned precautions are given in table IV. The total exposure of the crew during their professional career years would in this way become substantially lower than one-fourth of the maximum permissible exposure for continuous occupation over a period of 50 years.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 4, 1962.

APPENDIX

SYMBOLS, DEFINITION OF DOSE UNITS AND TERMS USED IN RADIOBIOLOGY, AND PROTECTION GUIDES

Symbols

E	energy in electron volts (1 ev = 1.6×10^{-12} erg, 1 Kev = 10^3 ev, 1 Mev = 10^6 ev, 1 Bev = 10^9 ev)
P_{max},P_{min}	number of hits/cm^3 emulsion/day during solar maximum and minimum years, respectively
Z	atomic number or charge of nucleus in units of elementary charge
λ	geomagnetic latitude

Definitions

The following definitions of dose units and radiobiological terms are used:

r: 1 r (roentgen) is the amount of X-radiation which produces 2.08×10^9 ion pairs (one electrostatic unit of charge) per cubic centimeter of standard air (energy absorption, 83.7 ergs/g of air). This amount of X-radiation will deposit much more energy in 1 gram of material of higher Z-number (for example, bone) than in 1 gram of soft tissue, water, or air, especially if the X-radiation is soft. Since the amount of energy absorbed per gram or the number of ion pairs per gram is, to a first approximation, a measure of the biological effect, the absorbed energy per gram produced by any kind of radiation (also particle radiation) is at present commonly used as a measure of the physical dose. The units of this absorbed dose are rep or rad.

rep (roentgen equivalent physical): 1 rep is defined here as 93 ergs/g of absorbed energy. This energy is absorbed by 1 gram of soft tissue or water exposed to 1 roentgen of X-radiation ($E \geqq 200$ Kev).

rad: 1 rad = 100 ergs/g of absorbed energy.

RBE (relative biological effectiveness): Low-energy protons ($E < 15$ Mev), α-particles and heavier ions, which ionize more densely along their paths have generally a higher biological effect than X-radiation at the same ionization or energy absorption per gram, that is, at the same rep or rad dose. Hence, for particle radiation this physical dose has to be multiplied by the RBE factor which is dependent not only on the specific radiation, but also on the specific effect and organ in question, and on the mode of application, to obtain the biological dose in rem units (roentgen equivalent men):

$$\text{Dose in rem} = \text{Dose in rep (or rad)} \times \text{RBE}$$

The RBE factor can have values from 1 to 20, the high values for relatively slow and heavily charged particles. Because of their low specific ionization, penetrating high-energy proton beams in the energy range from 10 Mev to 1 Bev have, in general, only an $\text{RBE} \leqq 1.5$. This value refers to bone marrow, intestinal, and general somatic damage, if secondaries can be ignored.

Dose limits:

450 rem: Acute total body dose which is considered lethal for 50 percent of men exposed to it during a period up to about 1 day and is designated as LD_{50}

150 to 200 rem: Average acute total body dose for radiation sickness

80 to 100 rem: Critical (total body) dose which produces light symptoms of radiation sickness for 5 to 10 percent of those exposed to it in a period of 1 day or less.

C: 1 C (curie) is the amount of radioactive material that exhibits 3.7×10^{10} decays/sec, the same number of decays as 1 gram of Ra^{226}; 1 μC (microcurie) = 10^{-6}C = 3.7×10^{4} decays/sec corresponds to 10^{-6} gram of Ra^{226}.

Protection Guides

According to the recommendations of the Federal Radiation Council (see ref. 10), the following radiation protection guides are adopted for normal peacetime operations:

Type of exposure	Condition	Dose,[a] rem
Radiation worker:		
(a) Whole body, head and trunk, active blood forming organs, gonads, or lens of eye	Accumulated dose	5 times number of years beyond age 18
	13 weeks	3
(b) Skin of whole body and thyroid	Year	30
	13 weeks	10
(c) Hands and forearms, feet and ankles	Year	75
	13 weeks	25
(d) Bone	Body burden	0.1 microgram of radium 226 or its biological equivalent
(e) Other organs	Year	15
	13 weeks	5
Population:		
(a) Individual	Year	0.5 (whole body)
(b) Average	30 years	5 (gonads)

[a]Minor variations here from certain other recommendations are not considered significant in light of present uncertainties.

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