Radiation Safety in High-Altitude Air Traffic

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Results of an experimental and theoretical study on dose equivalent rates at high altitudes are presented. The flight personnel flying 500 hours per year at SST cruise altitude in high latitudes (maximum of radiation) would be exposed to less than 14% of the maximum permissible dose rate (MPD) for radiation workers (5 rem/yr), averaged over the solar cycle. One-half or more is due to energetic secondary neutrons that are penetrant and highly biologically effective. Passengers would, in general, be exposed only to the low-level galactic cosmic rays, except for a relative few who encounter rare, intense, and energetic solar-particle events. If the airplane descends to subsonic altitudes during events such as that of Feb. 23, 1956—the most intense and unique giant energy event of the last 35 years—passenger exposure even then remains at or below permissible levels (0.5 rem for the general population). Systems of radiation monitoring are briefly discussed which will prevent false alarms and which would be useful in disproving overexposure in potential malpractice suits against the airlines. In subsonic jet transports the exposure of the crews is lower by a factor 3 to 4; for passengers it is about the same for the same distance traveled. Solar events, except for giant energy events, will yield only a minor fraction of the MPD of the general population.

Introduction

HIGH-ALTITUDE commercial airplanes, as they are available for the near future, will cruise at altitudes of 18-20 km (60,000-65,000 ft). At these altitudes only about 6% of the mass of the atmosphere (60 g/cm^2) is left above the airplane, and this affords little protection against space radiation such as galactic and energetic solar cosmic rays. The buildup of highly biologically effective secondaries may even have the consequence that the biological dose at high altitudes exceeds that of the primaries.

In the following paper, this problem and the problem of radiation safety in high-altitude commercial flight is reviewed, with particular attention to the most biologically important of these components—the fast (0.1-10 MeV) and energetic (10-500 MeV) secondary neutrons, which penetrate deep into the atmosphere. The results of previous investigations [1-15] on dose equivalent (rem†) rates in supersonic (SST) and subsonic altitudes and on the contributions of neutrons, were subject to large uncertainties. This is especially true in high latitudes, where maximum intensities occur and where no prior measurements have been made.

The question has its bearing on radiation safety since the neutrons may, at intense high-energy solar events (very rare events), produce biological doses at and even below SST altitudes that are in excess of the maximum permissible standards.

To solve this kind of a "thick shielding" problem, as it may be called here, and also to determine flux-to-dose-rate conversion factors, theoretical work on cross sections and transport of neutrons from protons and neutrons incident on light-element nuclei (e.g., hydrogen, oxygen, nitrogen, aluminum) had been undertaken as early as 1962 with others by Oak Ridge's Neutron Physics Division under NASA-AEC sponsorship. From 1965 (galactic cosmic ray maximum) until 1971, furthermore, a comprehensive experimental program was conducted by NASA Langley in conjunction with the Cosmic Ray Project team of New York University; using high-altitude balloons and airplanes, this program measured tissue-absorbed doses and fast neutrons, especially in high latitudes, and their variations with altitude and solar activity. The experiments were supplemented by theoretical studies, with others at Langley, on nucleon and meson cascades from incident high-energy protons (0.1-10 GeV) on the basis of Oak Ridge's secondary production cross sections, the results of which were well in agreement with the dose- and fast-neutron distributions from galactic and high-energy solar cosmic rays measured in the experiments.

The results of these experimental and theoretical programs are summarized in this report insofar as maximum dose equivalent rates down to subsonic jet altitudes from cosmic rays and, in particular, high-energy solar events are concerned. More comprehensive surveys of the measurements and theoretical results, including their relevance to cosmic ray research, and a more detailed comparison with the radiation protection guidelines have been presented in committee meetings and conferences from 1968,[12,16-22] and a NASA technical note.[23] The global neutron distributions and their variations with solar activity are treated by the NYU cosmic ray project team, led by S. Korff and R. Mendell.[24-26]

Since during at least one event [the intense giant energy (GeV) event of Feb. 23, 1956, of solar cycle 19 (Jan. 1954 to July 1964)] the maximum permissible dose (MPD) for passengers would have been exceeded at SST cruise altitude, evasion measures and monitoring systems are discussed that would: 1) assure compliance with the guidelines; 2) avoid unnecessary preventive measures or delays from more frequent, unpredictable, low-intensity events; and 3) by disproving claims of overexposure, protect the airlines from legal liabilities.

Radiation Safety

We will take the designation "radiation safe" to cover the maximum permissible doses (MPD's) for peacetime operations as they are established by the International Commission for Radiological Protection (ICRP) and the U.S. Nuclear Regulatory Commission.[27-29] These maximum permissible doses from external radiations applicable to crew and passengers are briefly summarized in Table 1.

The doses are given in rem, instead of in rad. We may recall that the rad measures only the energy absorbed per gram or the "absorbed dose" (1 tissue rad = 100 erg/gr tissue). For a given amount of absorbed energy, heavily ionizing charged nuclei and neutrons do much more biological damage than x-rays (photo and compton electrons), outer electrons, gamma rays, energetic protons, or other lightly ionizing particles, for which rem and rad are the same. The rem is the dose corrected for this increased biological effectiveness. The "quality" factor of the specific radiation, i.e. the ratio of rem over rad, is a function of the linear energy transfer (LET), i.e. ion

Received March 4, 1977; revision received May 9, 1977.

Index categories: Safety; Space Medicine (including Weightlessness, Radiation Effects, Psychology, etc.); Atmospheric and Space Sciences.

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†Roentgen equivalent man.

Table 1 Maximum permissible doses (MPD's)

Radiation workers:	
Whole body	$\frac{5\text{ rem}}{\text{yr}} = \frac{0.6\text{ mrem}}{\text{hr}}$ (for pregnant radiation workers, 0.5 rem/yr)
Population:	
Individual	$\frac{0.5\text{ rem}}{\text{yr}}$ (total of 5 rem up to age 30)

density along the tracks, and is conservatively established by the ICRP for radiation protection guidelines. For safety reasons the quality factor is, in general, defined higher than the relative biological effectiveness factor (RBE) or the real biological effect found in animals and man. For fast and energetic neutrons as they occur at high altitudes, the dose equivalent, or rem, is about 10 times the absorbed dose.

The main reason that the uncharged neutrons penetrate relatively unimpeded deep into the atmosphere and are, on the other hand, strongly absorbed and biologically effective in tissue, is that the neutrons have the same low mass of protons (hydrogen atoms, H) and therefore lose very little energy in elastic collisions with the heavy N and O atoms of the air; however, in each collision with the many protons in tissue (H_2O, hydrocarbons, etc.), they impart, on the average, half of their energy, until they finally come to rest. The "recoil" protons are heavily ionizing at the ends of their paths and are, therefore, highly biologically effective. Fast and energetic neutrons also produce more "stars" that are the sites of inelastic nuclear collisions and from which heavily ionized "prongs" of reaction products and further neutrons emanate, than do protons of the same energy, because they are not hindered by the Coulomb barrier around the nuclei.

It may be noted in Table 1 that the average MPD for radiation workers is 10 times higher (5 rem/yr) than the MPD for individuals of the general population (0.5 rem/yr). The reason is that radiation workers are a small group of adults. The general population encompasses children, including infants—even the fetuses in pregnant women—who are much more sensitive to radiation. In fact, the guidelines for the general population are even more restrictive. "Total of 5 rem up to age 30" means that, on the average, only 0.167 rem/yr is permissible up to age 30. Thus, not for every year is 0.5 rem allowed. The average age limit for human reproduction is 30 years. The low dose for the general population to age 30 is established to forestall an increase of mutations in successive generations of the population and also to prevent late effects during the individual's lifetime.

For high-altitude flight, the crew or flight personnel are equated to radiation workers because they are adults, and the passengers are equated to the general population. Thus, the following two numbers may be noted:

For the crew—5 rem/yr on the average over long periods, say 10-30 yr, are permissible (for pregnant crew members only 0.5 rem/yr are permissible).

For passengers—a maximum of 0.5 rem/yr in single years, or one time in a single year, is considered permissible, provided a total of 5 rem up to age 30 is not exceeded.

Measurements and Derivation of Dose Equivalent Rates

Through the early phase of solar cycle 20 (from 1965-1968), twenty balloon launches, five each year, provided by the Skyhook Organization of the Office of Naval Research, were conducted from Fort Churchill, Hudson Bay, Canada (magnetic latitude ≈ 69 deg) up to altitudes of 40 km (135,000 ft); in addition, in Nov. 1965 a latitude scan at 10 km (35,000 ft) altitude was made via participation of Langley and New York University on the 65-hr globe-circling flight over both poles by a Boeing 707 of the Rockwell Corporation.‡ Airplane flights to higher altitudes were conducted with the U2 in 1966 and 1967 and, in particular, with a B57F from Fairbanks, Alaska, from 1968-1971, the latter provided by the Air Force Chief of Operations, Air Force Weather Service 9th Weatherwing. After 1968 the flights were conducted simultaneously with the FAA-AFWL High-Altitude Radiation Environment Study (HARES). The generous support of the Air Force, with approximately 300 flights in the framework of training and other research programs and with standby and all-weather flights during solar events according to a specially developed alert plan, made it possible to follow the variations of the cosmic-ray-produced neutrons closely and to measure, for the first time, neutrons produced by solar flare particles at SST altitudes. In addition, the ESSA (NOAA) Solar Activity Forecast Center in Boulder, Colo., was of great help in providing continuing and timely information on solar activity over many years; this was indispensable for proper timing of the launches during solar events and Forbush decreases. Unfortunately, the solar events during these years were rather weak. The experiments had to be discontinued in June of 1971, because of withdrawal of funds connected with SST research, before the very intense solar event series, which was expected for the decreasing phase of the solar cycle, occurred in Aug. 1972.

We note that most flights were made in high magnetic latitudes. The reason is that we are primarily interested in maximum doses and these occur at magnetic latitudes above ±55 deg. These latitudes also contain the North Atlantic and Canadian air routes and parts of the routes from Los Angeles to Europe, from the U.S. to Moscow and China; the shortest route from Washington to Peking passes the proximity of the magnetic North Pole.

Below 55 deg magnetic latitude the doses fall off rather rapidly, because the magnetic field of the Earth deflects the cosmic ray particles at lower latitudes. The dose equivalent rates from galactic cosmic rays decrease by about a factor of 6 toward the Equator, according to our measurements.

The instruments used in these flights were fast-neutron spectrometers, which measured the neutron fluxes as a function of energy in the interval 1-10 MeV, and tissue-equivalent ion chambers. The detection of neutrons with the spectrometer was based on discrimination of pulse shapes in a liquid scintillator surrounded by a plastic scintillator, the latter for the exclusion of charged particles.[30] The spectrometers were developed by R. Mendell and S. Korff, New York University. Mrs. Mendell also supervised the neutron measurements. The ion chambers with tissue-equivalent walls were designed and built by AVCO Corporation, Tulsa, Okla., according to specifications of M.F. Schneider, Air Force Weapons Laboratory,[31] and supplemented with recorders by R.R. Adams of NASA Langley Research Center, who supervised the calibration, measurements, and evaluation. The instruments in some flights were first suspended in free air and then inside spherical phantoms (15-cm radius) of tissue-equivalent material, representing the human body, in order to derive the dose equivalents in extremities (i.e., small tissue samples, represented by the sensors) and in the depth of the body.

The ion chamber with tissue-equivalent walls measures the tissue-absorbed dose (rad) from all particles, i.e., that from primaries, secondary protons, mesons, electrons, and protons, plus that from neutrons, so far as these radiations penetrate to the high flight altitudes; metal-walled ion chambers would not have measured the tissue-absorbed doses of neutrons adequately. Our ion chamber does not, however, measure the dose equivalent (rem) rate. To arrive at that we

‡The participation was arranged by S. Korff, Director of the NYU Cosmic Ray Project.

have to add the "damage increment" rem minus rad (rem − rad) from those particles that have a higher relative biological effectiveness than x-rays or a quality factor greater than one, that is, essentially, the rem − rad from the fast and energetic neutrons (recoil protons and neutron stars in tissue) and that from proton-produced stars (the latter is a small contribution).

The rem − rad from both neutrons and protons can be calculated using known flux-to-dose rate conversion factors,[32-37] if the neutron and proton energy spectra in jet altitudes are known. To obtain the approximate shape of these spectra, especially in the high-energy range up to 500 MeV (the neutron spectra are only measured in the range 1-10 MeV), Monte Carlo calculations of J.W. Wilson in Langley, applied to incident galactic and energetic solar protons of up to 10 GeV energy, were finally used[16-20,23] (see Appendix). Although the code treats only incident protons—the secondary particles from heavy primary (He,...Fe,..) collisions with air (N, O) are as yet not known—these calculations yielded the shape of the fast neutron spectra, their maximum at SST altitudes, and their large penetration depth all well in agreement with those measured in the galactic cosmic ray experiments (see Fig. 1b). Since in the case of galactic cosmic rays the percentages of incident nucleons bound in heavy primaries is substantial (≈40%), the theoretical neutron spectra were correct only up to a factor and had to be normalized with respect to absolute intensities by the measured fast neutron spectra of one altitude.

The proton code, without adjustment by measurements, yields intensities for the secondary neutron spectra that are apparently about 15-20% too high as estimated by comparison with measurements of galactic cosmic-ray-produced neutrons and also, in one case, with those from energetic solar cosmic rays (weak high-energy event of March 30 and 31, 1969.[20,23]) It was nevertheless applied without correction to such solar events during which no measurements of neutrons within the atmosphere could be made, as during the intense and most important giant and medium energy events of Feb. 23, 1956 and Nov. 12 and 13, 1960 (see Figs. 4 and 5). Only realistic upper limits of doses are sought in this study. For this purpose values 15-20% too high, which furthermore will compensate to a large degree for neglected contributions from heavy primary-produced nucleons, appear satisfactory as long as the penetration to subsonic jet altitudes is reflected within this limit.

Maximum Exposure of High-Altitude Jet Occupants and Comparison with MPD's

To obtain maximum exposures of SST and subsonic jet occupants and compare these with the MPD's, some of the results obtained at high latitudes for galactic and solar cosmic ray dose rates as a function of altitude will be presented.

Galactic Cosmic Ray Dose Rates

Galactic cosmic rays are of low intensity; however, they are always present. Their intensity varies by a factor of about 2 in the high-energy range (>3 GeV/nucleon) and by factor of about 4 in the lower energy range (0.1-1 GeV/nucleon) during the 11-year sunspot cycle.

In Fig. 1a, the circles show the measured dose rates as a function of altitude. The scale is on the right-hand side, and is given in rads, not corrected for biological effectiveness. This dose rate leveled off above 24-km (80,000-ft) altitude in all years for which measurements were made. The squares show the fast-neutron flux measured separately. The scale is on the left-hand side. Note that the neutron flux has a maximum just at SST altitudes;Fig. 1b compares the altitude dependence with that obtained theoretically by J. W. Wilson.

Figure 2 shows the biological dose rates or dose equivalent rates in mrem/hr derived from measurements made with the ion chamber and neutron spectrometer and from the neutron

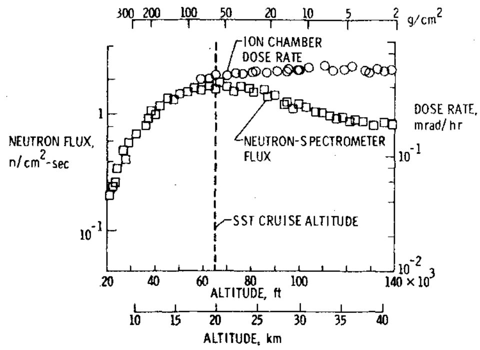


Fig. 1a Galactic cosmic rays. Balloon ascent to 43 km, Fort Churchill, 69 deg geomagnetic latitude, July 15, 1967.

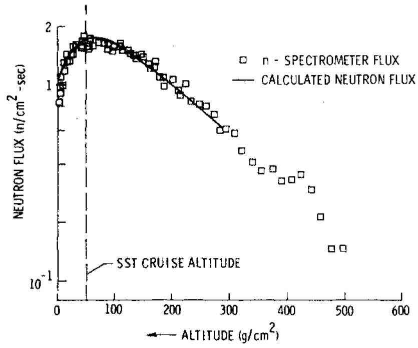


Fig. 1b Altitude dependence of fast neutrons, obtained by Monte Carlo calculations (solid line) in comparison to the measurements.

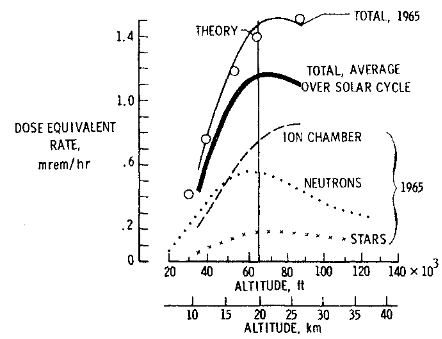


Fig. 2 Body depth doses from galactic cosmic rays.

extrapolations. Consider first the lines labeled 1965. The dashed curve shows the rad contribution of all the particles; the dotted line shows the contribution rem-minus-rad of the neutrons, containing also the stars produced by neutrons; and the ×'s show the contribution rem-minus-rad of the stars produced by charged particles, which are sites of nuclear reactions with extensive local damage to the cells, as are the stars produced by neutrons. It may be mentioned that the dose equivalent rate due to neutrons, derived from our measurements and calculations, is about 4 times higher than that estimated in the ICRP Task Group Report of 1966[10] (for a detailed comparison see Ref. 23). In fact, the fast and energetic neutrons produce about one half of the total dose equivalent rate.

The light solid line is the total dose equivalent rate as a function of altitude, which again indicates a maximum at about SST altitude. The circles labeled "theory" on the total dose curve for 1965 were calculated starting from the approximately known cosmic ray proton spectrum in space, using the aforementioned Langley developed computer program to determine the dose at various depths in the atmosphere. The fluxes were normalized by the measured fast-neutron flux at SST altitude. It may be noted that the curve is labeled 1965. That was near sunspot minimum, when the galactic cosmic ray flux is a maximum. The average over the 11-year cycle would be less, about as shown by the heavy line. The average dose rate is about 1.2 mrem/hr at SST altitude.

Thus, we obtain the following results: if the crew flies 500 hr/yr in SST cruise altitude, their average dose rate due to galactic cosmic rays would be about 500×1.2 mrem/hr = 0.6 rem/yr, or only about 12% of their maximum permissible dose rate.

The gross of passengers, who may cross the North Atlantic only a few times a year, not encountering solar events, would be exposed in 2 hr at cruise altitude to only about 3 mrem, which is negligible in comparison with 500 mrem, or 0.5 rem, which is their maximum permissible limit per year.

Solar Cosmic Ray Dose Rates

Solar cosmic rays or solar particle events observed on Earth, accompanying some, but not all, flare outbursts on the Sun, are transient particle showers (duration 8-24 hr); however, in some rare cases their intensity in the energy range of about 100 MeV, or sometimes even greater than 1 GeV, may be up to 1000 times higher than that of galactic cosmic rays.

In Fig. 3 the two curves on the left correspond to a high-energy event of very low intensity that occurred on March 30-31, 1969—the only event during which the measurement of the neutron increases at SST altitude succeeded. The increments of intensity or dose rate, respectively, (ordinates) are plotted against time in hours (abscissa). The fast-neutron intensities at this altitude calculated with the Langley code from the primary proton spectra—measured with rockets at high altitudes by Russian researchers—were within 20% in agreement with our measurements. The dose equivalent increment in altitude was derived from the neutron and absorbed-dose measurements with the help of this code, as described for galactic cosmic rays.

The neutron monitor on the ground showed only a 5% increase over its background (the background is due to the steady flux of galactic cosmic rays). The airplane measurements at SST altitude, however, yielded about a 90% increase in biological dose rate, or nearly 20 times more than the neutron increment on the ground.

The event on the right is the famous giant event of Feb. 23, 1956, which is the largest giant energy event observed in at least 30 years. (Other intense giant energy events occurred on Feb. 28, 1942, and March 7, 1942; July 25, 1946, and Nov. 19, 1949, maximum two times per solar cycle.) In Feb. 1956, instead of 5%, an increase of 3600% or 36 times galactic cosmic ray background, was observed on the ground (in New Hampshire). No measurements at altitude could be made in 1956 during the main phase of the event. To arrive at a rough estimate for the dose rate at SST altitude, for comparison with the theory, we use the same factor of only about 20 that was found for the smaller flare, and we obtain an increase of 720 times that of March 1969. This represents a dose rate at SST altitude of over 1000 mrem/hr, or 1 rem/hr, at the beginning of the event.

We compare this experimentally determined high dose rate, which would result in an overexposure of passengers staying for 2 or more hours at SST cruising altitude, with the more rigorous calculations made using the Langley Code for this event. The calculations for the Feb. 1956 event started by using the proton fluxes and energy spectra above the atmosphere in space estimated by Meyer et al.,[38] Fowler and Perkins,[5] Schaefer,[2] and the NASA Goddard Cosmic Ray Team,[39] from ground measurements over a wide latitude range in the period of maximum intensity and energy, and also extrapolated back from balloon measurements made by Winkler and van Allen 17 and 19 hr later.[40,41] These estimated "prompt" spectra in the first hours lie in the broad strip indicated in Fig. 4. The estimates are extrapolated to lower energies by the dashed lines. The border lines are called upper and lower limits of the prompt spectrum.

Figure 5 shows the results of these dose calculations for different altitudes. The peak dose equivalent rate for Feb. 1956 at SST altitude is found to be between 0.5 rem/hr and 3 rem/hr, which is in fair agreement with Fig. 3. The large difference between the upper and lower limit is due mainly to the uncertainty in the lower-energy parts of the prompt spectra ($E \approx 1$ GeV), which were cut off by the magnetic field of the Earth below $\lambda_{mag} \approx 55$ deg, the highest latitude where ground neutron monitors were situated at that time. The peak dose rate at subsonic altitude (9 km) is found to be ≤ 0.45 rem/hr. Because of the rapid intensity decrease, the accumulated dose will not be larger than 0.45 rem.

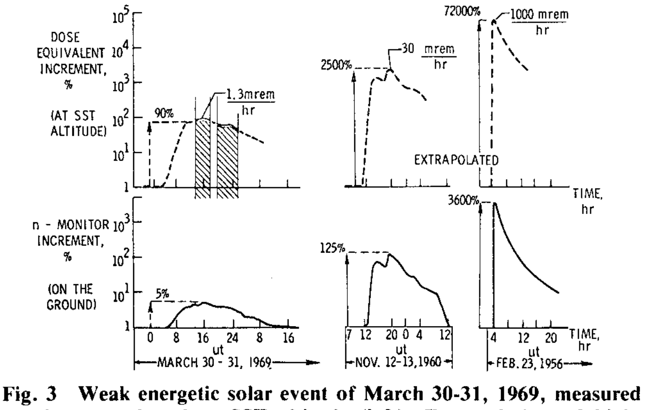
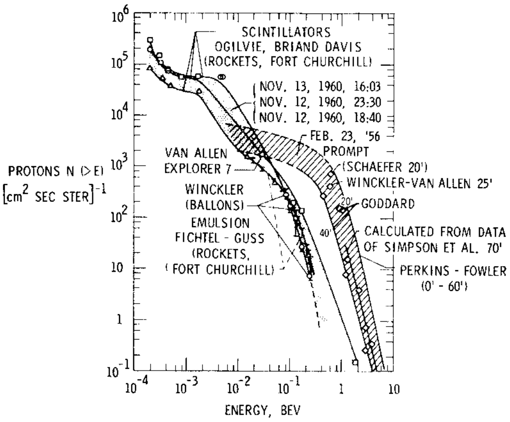


Fig. 3 Weak energetic solar event of March 30-31, 1969, measured on the ground and at SST altitude (left). Extrapolation of high-altitude doses for the very intense high-energy events of Nov. 12-13, 1960, and Feb. 23, 1956.



THE NUMBERS 20', 25', ... ARE THE MINUTES AFTER SOLAR COSMIC RAY ONSET, OBSERVED ON EARTH 0350, FEB 23, 1956

Fig. 4 Flare particle spectra.

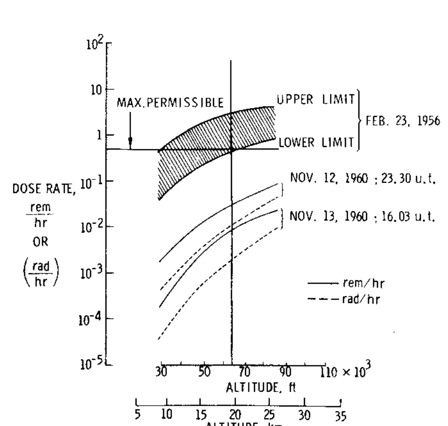


Fig. 5 Calculated solar flare doses.

Similar dose calculations have been made, in part prior to 1969, for the most significant of the 60 solar events of the particularly active solar cycle 19—in particular, May 10, 1959; July 10, 14, and 16, 1959; Nov. 12 and 15, 1960; July 12 and 18, 1961—starting with the energy spectra in space derived from balloon, rocket, satellite, riometer, scattering-network, and sea-level neutron-monitor data, by this author.[42,43] The second largest event was that of Nov. 12-13, 1960, which is seen at two different times in Figs. 4 and 5. The dose equivalent rates are only about 30 to 50 mrem/hr at SST altitude. It should be noted that, during low- and medium-energy events, it is mainly the neutrons that penetrate to supersonic and subsonic altitude, while the charged particles are largely absorbed at higher altitudes. At 9-km altitude, the dose rate for Nov. 12 at 23:30 universal time (u.t.) is lower by a factor of 15, that is, about 2 mrem/hr.

Galactic plus Solar Cosmic Ray Dose Rates for Crew and Passengers, and Evasion Measures

On the basis of these measurements and calculations for solar events, conclusions may be drawn on the average exposure of the crew from solar cosmic rays assuming, conservatively, that the crew was exposed at SST altitude to the maximum phase of each major event of solar cycle 19. The results are given in Fig. 6. One sees that the contribution of all major events, except that of Feb. 1956, is very low. If the Feb. 1956 event is included, an upper limit of 0.3 rem/yr is obtained as the average contribution per year from solar events of one cycle. Of course, in none of the single years was the maximum permissible dose rate of 5 rem/yr for the crew reached, even if the airplane had remained at cruise altitude during the events. When the previously given galactic cosmic ray average dose rate of 0.6 rem/yr is added, the total is 0.9 rem/yr from solar plus galactic cosmic rays. This is the average over the solar cycle. If, in order to reduce the exposure of passengers, the evasion measure of descent to 9 km had been taken in the February event, the average exposure of the crew would have totaled 0.7 rem/yr, or 14% of the MPD for radiation workers, and a maximum of 1.2 rem/yr, or 24%, if a Feb. 1956 event were to be encountered. It might be added that this exposure on high-latitude routes is still slightly higher than the exposure of 80% of the radiation workers in the nuclear industry, who are actually exposed to only about 10% of the MPD for radiation workers. The exposure per year on high-latitude routes is above the exposure limits for pregnant crew members (0.5 rem/yr). Female crew members should therefore be instructed about prenatal exposure risks. If they are or expect to be pregnant, they should, as a minimum precaution measure, not be given or take assignments on high-latitude routes during solar activity years.

The most important result so far is that, to the best of our present knowledge, the permissible exposure of passengers is exceeded if the SST flies at its cruise altitude during such giant events as that of Feb. 1956. This would be contrary to internationally accepted radiation protection guidelines.

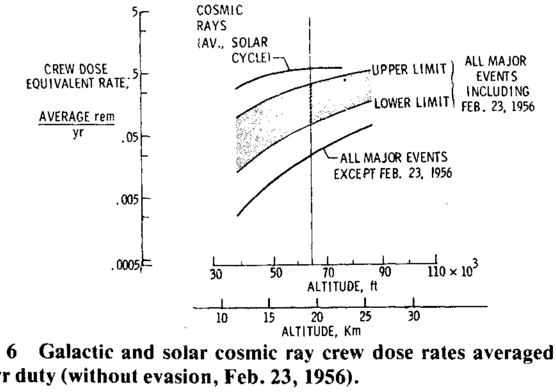


Fig. 6 Galactic and solar cosmic ray crew dose rates averaged over 10-yr duty (without evasion, Feb. 23, 1956).

Fortunately, because of atmospheric attenuation, timely descent to subsonic altitude during such events would reduce the conservatively high estimated accumulated dose by about a factor of 6 to below 0.5 rem, or below the MPD for passengers. In Fig. 4 it is seen that the maximum dose rate at 9 km (30,000 ft) would be 0.45 rem/hr. This is the dose rate at the peak of the event, a period of about 10-min. This fell very fast in the first hours (as in all high-intensity giant-energy events observed so far, see Ref. 23). The accumulated dose for any number of hours that the SST would remain at subsonic altitudes would not be more than 0.45 rem. Thus, such an evasion measure is sufficient to keep the dose within safe limits in such rare cases.

Our result is thus: that for the relatively very few passengers who might encounter major solar events (only 6 such major events occurred in cycle 19) at SST altitude, the exposure would be in the order of 100 mrem, i.e. 20% of their MPD; in the cases of intense giant energy events (only one or two per cycle occurred in the last 35 years), the doses would not have exceeded the MPD, or 100%, if the airplane descended and remained at 9 km altitude during the event. Since it is desirable to hold any exposure as low as possible, the airplane may also descend to lower altitudes in such cases as November 12, 1960 or August 4, 1972 (cycle 20), although during this latter extreme intense medium energy event the dose at SST altitude would have reached only a fraction of the MPD for passengers.

So far as exposure during subsonic jet transport is concerned, the crews would be exposed to only ⅓ or ¼ of the galactic cosmic rays experienced in SST flights, i.e. ≤ 0.4 mrem/hr, or in 500 hr at subsonic altitude, 0.2 rem/yr. The exposure from solar cosmic rays would be limited to that of giant-energy events, that is ≤ 0.5 rem/11 yr. Thus, in total, the exposure would be ≤ 0.25 rem/yr in the average over the solar cycle on high-latitude routes.

Passengers would be exposed to about to the same dose equivalent from galactic cosmic rays as SST passengers, because they spend about three times longer at subsonic cruising altitude if they travel the same distance. Solar events, except for intense giant-energy events, will yield doses of only a minor fraction of the MPD. A larger number of passengers will travel subsonic and will continue traveling frequently, and some may approach 250 hr/yr or even the 500 hr/yr flight time of the crews at subsonic altitudes. That is, they may become exposed, on average, to 0.125 or 0.25 rem/yr, which would be ¼ or ½ of the permissible limit for the general population (0.5 rem for single years). Thus, the subsonic transport would contribute more to the genetic burden of the population than a limited supersonic transport. Nevertheless, this contribution will be substantially below the permissible limit. Persons who fly frequently are still a small portion of the population pool, and those flying once a year or less would take only a negligible part of the dose of 5 rem in 30 years allotted to one generation.§

The results concerning the exposure of crew and passengers in cycle 19 are summarized in Table 2.

In summary, according to our present knowledge, "radiation safety" for passengers can be achieved if aircraft fly at subsonic altitude during the most intense events. In addition, for minimizing radiation exposure, airplanes on the ground may delay departure or may be rerouted until the maximum phase of the event is over.

§In June 1977, a report "Cosmic Radiation Exposure in Conventional Subsonic Air Travel" (FAA-AM-77) prepared by Charles A. Sondhaus and Roger W. Wallace for the FAA Advisory Subcommittee on Radiation in Conventional Jet Travel appeared, that considers genetic and late effects. It confirms, on the basis of comprehensive statistics, the conclusion that the genetic burden of the U.S. population pool from radiation in conventional jet flight is at present (and will be in the foreseeable future) far below maximum permissible levels and that it is unlikely that it will approach doses that are received at present from other sources.

Table 2 Maximum dose equivalents of SST occupants (on routes 55-deg magnetic latitude, evading to subsonic altitude at very rare intense giant-energy solar events)[a]

Exposure, rem/yr		Percent of MPD's
Crew:		
Average over solar cycle	0.7	14% of MPD for radiation workers (5 rem/yr)
Maximum per year	1.2	24% For pregnant crew members, 140-240% of their MPD (0.5 rem/yr)
Passengers:		
Large majority	<0.01	2%
Relatively very few individuals		of MPD for population (0.5 rem/yr)
From maximum six events in 11 years	≤ 0.10	20%
From one event in 11 years	≤ 0.45	90%

[a] In *subsonic* jet traffic, the crew dose equivalents are lower by a factor of about 3 to 4 (for the giant-energy solar events, the same). For passengers flying the same distance, the doses are smaller but approximately the same. Solar events, except intense giant-energy events, will yield doses of only a minor fraction of the MPD of the general population.

Monitoring Systems

To monitor the accumulated doses in SSTflights¶ and to assure timely evasion, the dose rate in the flying airplane must be known to the pilots in real time. The same should be the case for the airports to avoid, during solar activity periods, unnecessary groundings or rerouting of flights which may be initiated to minimize radiation exposure. During such periods, frequent series of solar events occur, mostly very weak events scattered over 1 or 2 weeks; thus, it would be very uneconomical to take preventive actions on the basis of incomplete information about the often unpredictable time of occurrence and strength of events.

The pilots can be provided with the necessary information by monitoring instruments in the airplanes that indicate the dose equivalent rate, including the neutron contribution and accumulated doses. Such instruments are used in the Concorde. The airports may be served by communication with the airplanes**, by optical, microwave, riometer, and neutron monitor observations on earth, and by satellite data, so far as these are available in real time. The latter requires a central institution which monitors and evaluates the data with respect to incident particle energy spectra and dose equivalent rates at high altitudes in approximately real time.

A system which would be able to independently serve both the aircraft and any ground stations which might be out of communication could be visualized using permanently operating communication satellites in synchronous orbit to directly measure the solar particle spectra and their directionality in space; calculating the corresponding complex radiation on the SST's in real time using the satellite or a ground station computer; and transmitting this information to ground and aircraft. A similar system using the SMS-GOES satellites was proposed by NASA Langley to NOAA (ESSA) and FAA in 1968. For transmitting data directly to a mobile station such as an airplane with a small antenna, more powerful transmitters would be required in the satellites.

¶This is recommended for all commercial flights above 48,000 ft (15 km) altitude, (ICAO recommendations 4/1 of SSTP II, Annex 6, Part I).

**During editing of this report, a NOAA Technical Memorandum ERL SEL-46: "A Study of the Capability for Rapid Warnings of Solar Flare Radiation Hazards to Aircraft" by Herbert H. Sauer and Garth H. Stonehocker, appeared, which treats the possibilities of communication between ground stations and aircraft during solar activity periods.

The safest solution might be, as proposed in the report of the FAA Advisory Committee for the Radiation Biological Aspects of the SST,[15] to use both on-board instruments and a satellite system.

A reliable satellite system will require further research on the impact zones of directional solar particle spectra, their dependence on magnetic field variations, and on the secondaries produced in air by helium and other heavy primary nuclei. These nuclei are observed to be present in significant proportions in some solar particle events and would contribute substantially to the absolute value of the dose equivalents at high altitudes.

In connection with the heavy-ion problem, the Langley Research Center is conducting theoretical studies[44-51] and experiments[52] at the Space Radiation Effects Laboratory. In addition, the Langley Research Center is conducting, in cooperation with ERDA experiments at the Lawrence Berkeley Laboratory's high-energy heavy-ion facility, experiments on heavy-ion reactions, especially in connection with neutron production. It is anticipated that a complete model for the interaction of particulate radiation with the Earth's atmosphere will be implemented in the next few years. From this model, the necessary parameters for the operation of a satellite monitoring system will be calculated.

In order to protect the carriers from legal liabilities, the monitoring systems should indicate, within known and sufficiently narrow error limits, the in-flight accumulated dose equivalents, including that of the fast and energetic neutrons which penetrate deep into the atmosphere and contribute half or more to the dose equivalent rates.

Appendix: Penetration Depth of Neutrons from Incident Protons of up to 10 GeV Energy – Heavy Primary Hits

Both the rem and rad in tissue can be calculated with known flux-to-dose rate conversion factors from the secondary neutrons and protons in the environment, if the energy spectra of these particles are known. So far as neutrons are concerned, we are interested only in those in the energy range 0.1-500 MeV; neutrons below 0.1 MeV can be neglected because of their small biological effect, and those above 500 MeV because of their small number. We have measured, however, only the neutron spectra in the energy range 1-10 MeV. The extrapolation, for galactic cosmic rays, of the neutron spectra to lower (0.1 MeV) and higher ($\simeq 500$ MeV) energies was first done with the spectral shapes theoretically extrapolated by Hess, Canfield, and Lingenfelter[53] from measurements in lower latitudes and altitudes (44 deg geomagnetic latitudes, in 1030- and 200-g/cm^2 atmospheric depth, that is, at sea level and 11.5-km altitude). These spectral intensities have their maximum in higher altitudes, and fall off faster with altitude and energy, than our measurements indicate. Also, the neutron spectra derived by Patterson et al. in 1959 and by Newkirk in 1963, after correction for differences in latitude and solar activity, are not in agreement with our fast-neutron measurements with respect to intensities and their altitude dependence.[10,23] Nevertheless, by using the theoretical shape for supplementing the measured neutron spectra in the 10 to 500-MeV energy range, approximate neutron doses in high latitudes down to subsonic altitudes could be derived. To obtain the relatively small proton-produced star contributions in tissue, star measurements in tissue equivalent nuclear emulsions at different altitudes by Davison[54] had been used in these first estimates. They turned out to be in agreement with the theoretical calculations mentioned later on.

So far as solar flare particle events are concerned (most frequently containing mainly protons of much lower energies, i.e., 10 to 200 MeV), no measurements at high altitudes of the biologically important components, especially neutrons, had succeeded until 1969. Thus, one was here dependent on theoretical estimates only, which were made with and without taking into account secondaries produced in the atmosphere, in the aircraft, and in man's body.[2-6,8-15] For low-energy events, calculations of neutrons and of their biological doses were developed by Flamm and Lingenfelter,[8] assuming idealized solar proton spectra (exponential rigidity spectra with characteristic rigidities $p<300$ MV or proton energies ≤ 47 MeV, which fall off rapidly in the higher-energy range) and by Leimdorfer and Crawford[13] for incident protons of energies ≤ 450 MeV. They could be applied to estimate dose equivalent rates down to SST altitudes (60-g/cm^2 atmospheric depth or 19-km altitude) for such low-energy events. They could, however, not lead to meaningful results for the dose rates from the more important high- and giant-energy (1 GeV$=10^9$ eV) events at those altitudes or even subsonic altitudes (9-12 km or 300-200-g/cm^2 atmospheric depth), or for the secondary spectra and doses from galactic cosmic rays of even higher energies (average 3 GeV/nucleon). The reason is that additional secondaries, especially neutrons, from primaries of >450 MeV energy are neglected. These primaries produce more and higher energy secondaries than the lower-energy primaries and thus contribute substantially to the buildup of the nuclear cascades and to their penetration power. The above theory for incident protons of <450 MeV energy, if it is applied to galactic cosmic rays (i.e., if all galactic protons of >450 MeV energy are treated as 450 MeV protons), yields at SST-altitudes values that are already too low by a factor 10, and would lead to even less realistic results at subsonic altitudes for galactic cosmic ray- or giant solar event-produced dose equivalents. As long as a theory for nuclear cascades from incident protons in the GeV range was not developed, only rough upper limits of dose equivalent rates produced by giant-energy events could be estimated[12] from the measurements for galactic cosmic rays.

In 1968, J.W. Wilson of Langley Research Center succeeded[16,18-20,23] in extending the nuclear cascade Monte Carlo calculations of Leimdorfer and Crawford for incident protons of less than 450 MeV to the GeV range by using the cross-sectional data for incident protons up to 2 GeV of Bertini[55] and extrapolating these cross sections semiempirically to 10 GeV. The code, applied to incident energetic proton spectra, described the development and penetration power of the neutron cascades from incident high- and giant-energy particles down to subsonic altitudes in satisfactory agreement with the measurements.

With respect to galactic cosmic rays, it may be emphasized that according to the Langley calculations the intensities of the energetic neutrons (10-500 MeV) fall off with $E^{-1.2}$ only, where E is the energy, and that this part of the neutron spectra contributes about 55% to the neutron dose equivalent rates at jet altitudes—substantially more than in the mentioned earlier estimates (e.g., Ref. 10). The dose rates derived with these spectra (normalized by the neutron measurements), using flux to dose rate conversion factors for small samples, also turned out to be well in agreement with the absorbed dose rates and dose equivalent rates measured directly with a LET spectrometer developed by Brookhaven National Laboratory, which was flown in the same flights.[56,15] It may be further noted that the Langley and Oak Ridge calculations in 1969 for dose equivalent rates during the Feb. 1956 giant-energy event[57] had identical results, if the same quality and flux-to-dose-rate conversion factors were used (for detailed comparison, see Ref. 23 Appendix).

Heavy primary hits or penetrations in tissue, and those of fragments heavier than protons, such as are produced in nuclear interactions with air, are neglected. According to measurements of Yagoda[58] and also according to unpublished measurements in the Langley program, the fluxes of heavy primaries and of energetic heavy fragments are practically zero at 18-20-km altitude (>60-g/cm^2 air shielding). The same results are obtained from the theoretical estimates of Schaefer.[59] Also, secondary mesons, electrons, and gamma rays are neglected because of their small contributions to the dose equivalent rates.[23]

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