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RADIOBIOLOGICAL ASPECTS OF THE SUPERSONIC TRANSPORT

(A report of the ICRP Task Group on the Biological Effects of High-Energy Radiations)*

(*Received* 25 *June* 1965)

INTRODUCTION

1. THE high cruising altitude of the supersonic transport (SST) will subject its occupants to larger amounts of cosmic radiation than are present at sea level or at altitudes attained by today's commercial jet aircraft. The passengers and crew of the SST will be exposed not only to increased amounts of gamma rays, but also to particulate radiations. Assessment of the health implications of the SST must, consequently, take into account the amount, relative biological effectiveness, and probable effect of these radiations, and the factors affecting the cumulative exposure and radiosensitivity of the exposed population.

2. The Task Group's appraisal of these questions is summarized in the following. Radiation doses which may be received by passengers and crew of the SST are compared with the maximum permissible doses recommended by the ICRP for radiation workers and the public. Although no attempt is made in this report to weigh the possible magnitude of the resulting risks from radiation in comparison with risks of other types to occupants of the SST, this is an aspect of the problem which may deserve consideration in evaluating the practical implications of this report.

CRUISING ALTITUDE OF SST

3. The altitude profile of the SST from takeoff to landing will not be known precisely until its performance has been studied in test flights, but estimates available from aircraft designers indicate that its cruising altitude will be somewhere between 60,000 and 80,000 ft. Because the absorption thickness (g/cm^2) of the atmosphere above the aircraft varies inversely with the altitude by a factor of more than 2 in this region (Fig. 1), the local intensity of radiation from sources outside the atmosphere can likewise be expected to vary appreciably.

4. Although it is recognized that future types of SST may fly at higher altitudes than the aircraft now under development, we have confined our attention in this report to altitudes of 60,000–80,000 ft. Extrapolation of our analysis to altitudes above 80,000 ft is not warranted because of the complexity of the radiation in the upper atmosphere. When and if higher transport flights are envisioned, the associated radiobiological problems should be reevaluated.

TYPES OF COSMIC RADIATION

5. Radiation from extraterrestrial sources, or cosmic rays, can be conveniently grouped into two categories, (1) galactic radiation and (2) solar radiation. Galactic radiation, which consists primarily of energetic protons, alpha particles, and to a lesser extent heavier nuclei (up to Z = 50), is derived from sources other than the sun and impinges continually on the

* This report was prepared for Committee 1 of the International Commission on Radiological Protection, and was received by the Committee on 20 April 1965. The report was prepared by a Task Group which was formed to consider the biological effects of high-energy radiations, with special reference to flight in the upper atmosphere. The members of the Task Group are: A. C. UPTON (Chairman), Oak Ridge National Laboratory, Oak Ridge, Tennessee; H. B. CHASE, Brown University, Providence, Rhode Island; G. L. HEKHUIS, Department of Defense, Washington, D.C.; R. H. MOLE, Medical Research Council, Harwell, Berkshire, England; H. B. NEWCOMBE, Atomic Energy of Canada, Ltd., Chalk River, Ontario, Canada; J. S. ROBERTSON, Brookhaven National Laboratory, Upton, L.I., New York; H. J. SCHAEFER, U.S. School of Aviation Medicine, Pensacola, Florida; W. S. SNYDER, Oak Ridge National Laboratory, Oak Ridge, Tennessee; C. SONDHAUS, California College of Medicine, Los Angeles, California; R. WALLACE, University of California, Berkeley, California.

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earth's atmosphere. By contrast, solar radiation is received intermittently from solar flares associated with sun-spots. The solar outbursts, which last a few minutes to several hours on the sun, emit protons and heavier nuclei which arrive at the earth over a period of hours or days, owing to partial entrapment of the particles in interplanatery space.[2]

6. The sun-spot activity varies cyclically (Fig. 2), the duration of each cycle averaging about 11 yr. The year 1965 is a year of nearly minimal activity ("quiet" sun). The next solar maximum is expected between 1968 and 1970. The sun's cyclic activity affects the intensity of galactic radiation as well as of solar radiation, owing to effects on interplanetary magnetic fields.

7. The flux of solar protons at the top of the atmosphere varies from flare to flare over several orders of magnitude and is not predictable except in a general way. Typically, the proton buildup at SST altitudes begins within half an hour after the maximum optical flare on the sun, reaches its highest intensity within minutes, and decays over a period of hours.

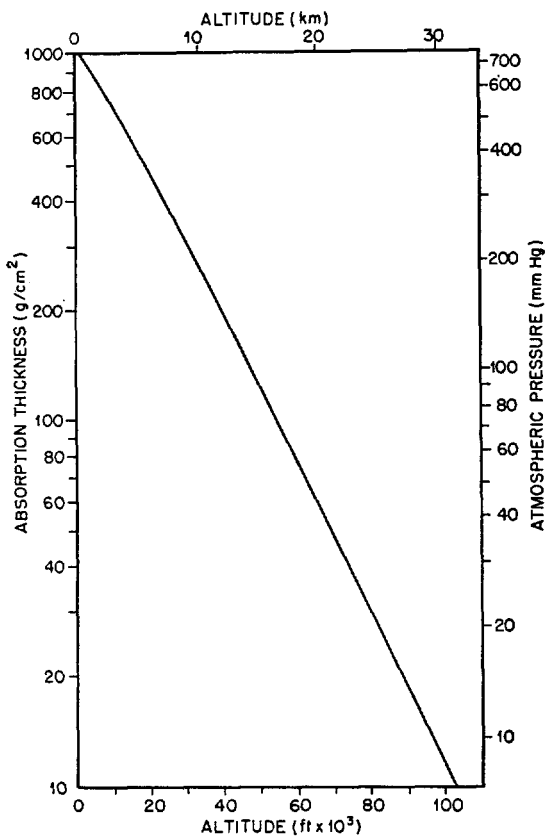

FIG. 1. Atmospheric pressure in relation to altitude.[1]

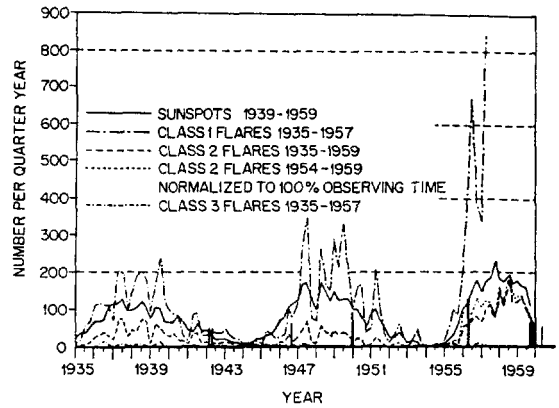

FIG. 2. Frequency and intensity of solar flares during solar cycles (from FOELSCHE and GRAUL, Ref. (16)). The cosmic ray events are indicated by the vertical bars, from which it will be seen that the numerous flares (i.e. the smallest ones, which are designated "Class 1") do not contribute appreciably to the cosmic ray intensity near the earth. For further details concerning the relation between solar flares and associated cosmic ray outbursts, see MCDONALD.[2]

GALACTIC COSMIC RADIATION AT SST ALTITUDES

Total ionization from charged particles and gamma rays

8. Measurements of the ionization of galactic cosmic rays have been carried out repeatedly.[3,4] At the top of the atmosphere, the total ionization increases from the equator towards the poles (Fig. 3) owing to the magnetic field of the earth, which deflects low-energy particles. Because of this screening effect, the so-called cutoff energy of a charged particle (i.e. the minimum energy it must have in order to reach the earth against the deflecting influence of the geomagnetic field) depends on the geomagnetic latitude, increasing from the poles to the equator. The associated latitude-dependence of the particle flux diminishes with decreasing altitude, however, and

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is almost completely absent at sea level, because only the hard component of the primary radiation, which is less affected by magnetic screening is capable of penetrating the atmosphere that deeply. The geomagnetic north pole is located at 78.5°N and 69.0°W, the axis of the magnetic dipole field of the earth forming an angle of 11.5° with the axis of rotation (geographic axis).

9. In years of high solar activity (e.g. 1958–1959), an interplanetary magnetic field is superimposed on the earth's field. Its screening effect, which is independent of latitude, approximates that of the earth's field at 54° magnetic latitude. As a result, the latitude effect for charged particles is essentially constant from 54° to 90° latitude, and so is the total ionization (Fig. 3). Because of the screening effect of the interplanatery field, soft primary radiation is virtually absent at all latitudes, and the altitude profile of ionization consequently reflects the buildup of secondaries in the upper atmosphere. This buildup, or "transition effect," reaches down to an altitude of about 70,000 ft, where it creates a maximum in the total ionization (Fig. 4).

10. In years of a quiet sun (e.g. 1954), the hard component of the primary radiation and its buildup are unchanged, but the soft component and its buildup are superimposed on it. Since the cutoff energy of the soft component drops continuously toward higher latitudes, reaching zero at the geomagnetic poles (Fig. 3), its secondaries penetrate correspondingly less

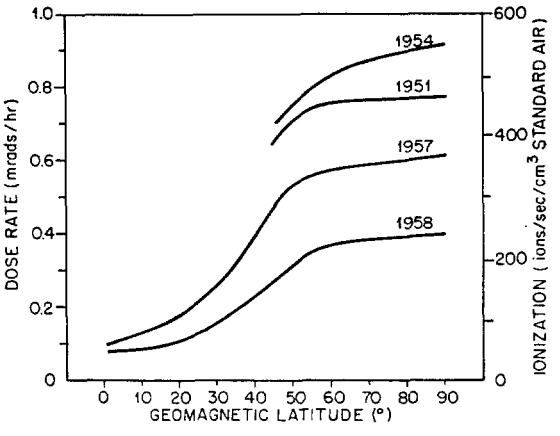

FIG. 3. Dose rate of galactic cosmic radiation at ~90,000-ft altitude in relation to geomagnetic latitude (from NEHER and ANDERSON, Ref. (4)).

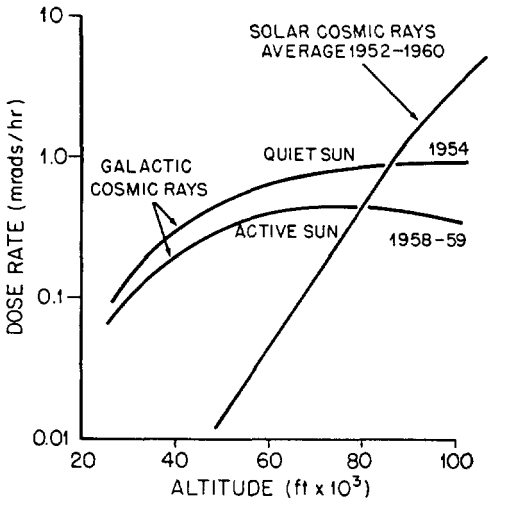

FIG. 4. Intensity of cosmic radiation in relation to altitude. Values shown are for high geomagnetic latitudes (from FOWLER and PERKINS, Ref. (3)).

and less deeply with increasing latitude. As a result, the altitude profile of ionization at the polar region shows a monotonic increase from sea level to the top of the atmosphere (Fig. 4).

11. The altitude profiles of maximal (quiet sun) and minimal (active sun) radiation intensities at high magnetic latitude suggest that dose rates due to galactic cosmic rays do not exceed 1 mrad/hr in the SST altitude region (Fig. 4). These estimates, however, will not be valid for occupants of the SST if attenuation of the radiation in the plane's fuselage is outweighed by production of charged secondaries. Nevertheless, even if a factor as high as 2 were assumed for this transition effect, which seems a conservatively high value, the maximum dose rate from this source would remain less than 2 mrad/hr at 80,000 ft.

Neutron component

12. Neutrons are produced by cosmic rays as secondaries from nuclear interactions in the atmosphere. The neutron flux near the top of the atmosphere may be expected to vary, accordingly, in relation to solar activity (2:1) and latitude (10:1).[5] The flux also varies in relation to altitude, building up to a maximum at or slightly under SST altitudes (i.e. at an

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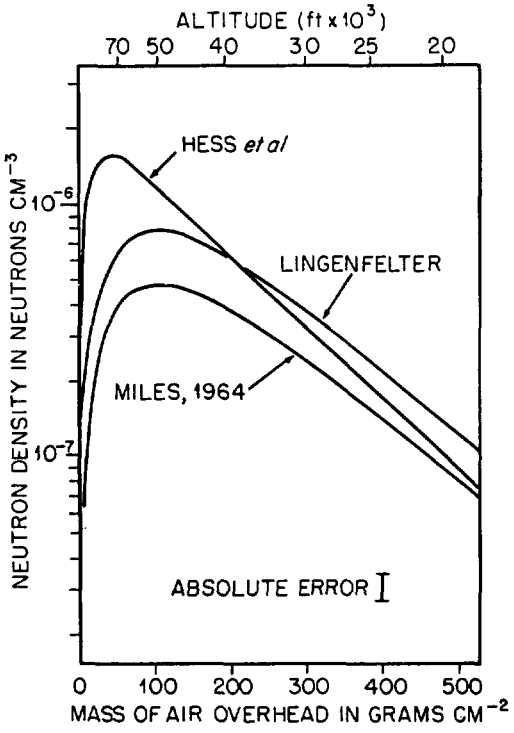

FIG. 5. Galactic cosmic ray neutron flux in relation to altitude (from MILES, Ref. (8)).

atmospheric pressure of about 100 g/cm², or 55,000 ft) and decreasing below this region (Fig. 5).

13. The energy spectrum of the neutrons is considered to be essentially constant throughout the atmosphere.[6] Fairly good experimental data on the neutron energy spectrum are available for altitudes from 40,000 ft down to sea level (Fig. 6), from which it may be calculated that the overall QF of these neutrons is approximately 8 (see para. 31 *et seq.*).

14. Even after correction for differences in latitude and solar activity, the available data on neutron flux at SST altitudes are not entirely consistent, the extrapolated values reported by HESS *et al.*[6] exceeding those based on measurements by other investigators (Fig. 5), for reasons which remain to be determined. For the present the extensive flux measurements of HAYMES,[7] which agree with other recent data[8] and with the earlier estimates given in *Handbook* 63 of the U.S. National Bureau of Standards,[9] appear to constitute the most satisfactory basis for estimating the neutron dose at SST altitudes (Table 1).

15. From the relation between flux density and altitude, as reported by HAYMES,[7] one can estimate the neutron dose rate at 41°N to be 7–9 μrad/hr in tissue at 50,000–80,000 ft (Table 1), neutrons of 0.1–100 MeV contributing the bulk of the dose equivalent.[6,10] From these values, the corresponding maximum dose rates at the magnetic pole may be estimated to be 14–32 μrad/hr in tissue (Table 1). Both sets of values, which are for a period of minimum solar activity, suggest that the neutron component may contribute only about 1–4 per cent of the total dose in the SST altitude region at solar minimum.

16. Although the total flux of galactic cosmic rays is higher by about a factor of 2 during the

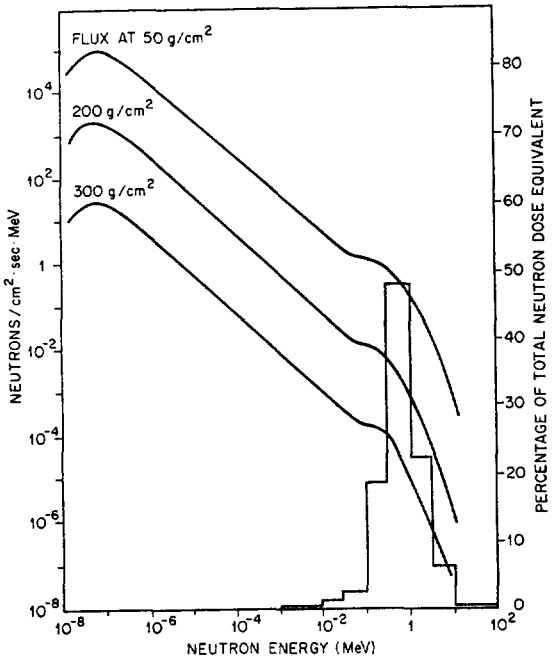

FIG. 6. Combined galactic cosmic ray neutron energy spectrum (from PATTERSON *et al.*, Ref. (10)) and the distribution of the dose equivalent resulting when the spectrum is multiplied by the values of RBE given in *Handbook* 63 of the National Committee on Radiation Protection and Measurements of the U.S. National Bureau of Standards.[9] The latter are based on the relation between QF and LET presented in Table 4.

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Table 1. Galactic cosmic ray neutron flux and dose rate in relation to altitude

Altitude (ft)	Flux density: Observed at 41°N (n/cm². sec)*	Flux density: Estimated at 90°N (n/cm². sec)†	Dose rate: at 41°N (μrad/hr)‡	Dose rate: at 90°N (μrad/hr)‡
0	5.4×10^{-3}	5.9×10^{-3}	4.3×10^{-2}	4.7×10^{-2}
10,000	4.0×10^{-2}	5.0×10^{-2}	3.2×10^{-1}	4.0×10^{-1}
20,000	1.6×10^{-1}	2.4×10^{-1}	1.3	2.0
30,000	5.0×10^{-1}	7.5×10^{-1}	4.0	6.0
40,000	7.9×10^{-1}	1.2	6.3	9.4
50,000	1.1	1.8	8.8	14.5
60,000	1.1	2.0	8.8	16.7
70,000	1.0	2.7	8.0	21.5
80,000	0.9	3.9	7.4	31.8

* Experimental data from HAYMES.[7]

† The values observed at 41°N were multiplied by factors from LINGENFELTER[5] to obtain the estimated values for 90°N latitude.

‡ Values in rad were calculated with flux density-to-dose conversion factors given in *Handbook* 63 of the National Committee on Radiation Protection and Measurements of the U.S. National Bureau of Standards.[9]

minimum of the solar cycle than during its maximum (see para. 10), this difference has not been reflected in neutron measurements made by eight different experiments at various times during the last half solar cycle.[11] These measurements show no upward trend with decreasing solar activity ; on the contrary, they suggest the opposite trend, but more observations during the imminent increase in solar activity will be needed to verify this.

17. Local production of neutrons in the aircraft material (e.g. for Ti, A = 48, Z = 22) may appreciably increase the neutron component, but will add only a small amount to the total dose. The difference between the number of neutrons produced per incident proton by Ti, and that produced in air or tissue will at most change the total dose by less than 2 per cent.

18. The extent to which neutron recoils contributed to the total ionization measured by NEHER and his co-workers is not clear. Since, however, their ionization chambers consisted of stainless steel and were filled with argon under high pressure, the relative contribution from neutron recoils in their chambers was substantially smaller than in tissue and conceivably might have been small even in absolute terms. Thus, the dose rates from neutrons mentioned above should be additive to the ionization dosage shown in Figs. 3 and 4.

LET *of radiation*

19. In penetrating to the altitude region of the SST, the heavy primaries at the upper end of the Z-spectrum are largely broken into smaller fragments through nuclear collisions. The depth of penetration of such primaries into the atmosphere is determined by their mean free path for nuclear collision, i.e. the distance in air over which their incident flux drops to $1/e$, or 37 per cent, due to nuclear collisions. The mean free path in air for C, N and O nuclei is about 30 g/cm² and for Fe nuclei about 15 g/cm². It is noteworthy, however, that the flux of heavy nuclei in the atmosphere decreases rapidly with decreasing altitude because many of the nuclei enter the atmosphere at oblique incidence. The pertinent relationship is described mathematically by the Gross transformation and the Gold integral, according to which the total flux at depths corresponding to 1, 2 and 3 mean free paths vertically from the top of the atmosphere decreases to 15, 3.8 and 0.2 per cent, respectively. At 70,000–80,000 feet altitude, the flux of heavy nuclei ($Z \geq 6$), as determined by emulsion measurements on balloon flights, was found to correspond to 0.96 ± 0.21 hits/cm³ of emulsion per day in 1958 and 0.68 ± 0.19 hits/cm³ of emulsion per day in 1959 at latitudes of 50–60°N.[12]

20. Nuclear collisions of heavy nuclei, as well

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*Table 2. Relative intensities of various types of galactic cosmic rays at 85,000 ft altitude**

Type of radiation	Charge	Relative flux	Mean value of ionization compared to that of H‡	Contribution to total dose (%)
H	1	5900	1	16
He	2	550	4	6
Li, Be, B	3–5	16	16	1
C, N, O, F	6–9	32	50	4
Ne-K	10–19	7	180	3
Ca-Fe	20–26	1	600	2
Secondaries of Z = 1†	±1	25,000	1	68

* From FOWLER and PERKINS.[13]

† The flux of secondaries shown is that calculated to make the total ionization in rads fit the observed increase with penetration to this depth in the atmosphere. The secondaries in question include mainly electrons, mesons and high-energy protons.

‡ Mean value of ionization per particle per unit length of track, as compared with that of protons of equal velocity; this gives an indication of the relative LET.

as those of primary protons, alpha particles and medium heavy nuclei, produce secondary protons, neutrons and alpha particles of low energy, which dissipate a portion of their energies at high LET's. The contribution of such radiations of high LET to the total dose that would be received by an occupant of the SST cannot be established exactly from available data. Estimates by FOWLER and PERKINS[13] suggest that it is not large even at 85,000 ft (Table 2); however their calculations neglect the neutron component and all secondaries of Z greater than 1. The distribution of LET, therefore, may be different from that implied by Table 2, especially at 60,000–70,000 ft, where the average energy of secondaries is appreciably lower than at 85,000 ft. Moreover, measurements with photographic plates indicate appreciable numbers of nuclear disintegrations ("stars") at 60,000–80,000 ft (Fig. 7), which are considered to be preponderantly neutron-induced at these altitudes,[14] although the numbers of multi-pronged "stars" shown in Fig. 7 are many times larger than those expected in tissue because of the high concentration of silver and bromine nuclei in photographic emulsion.

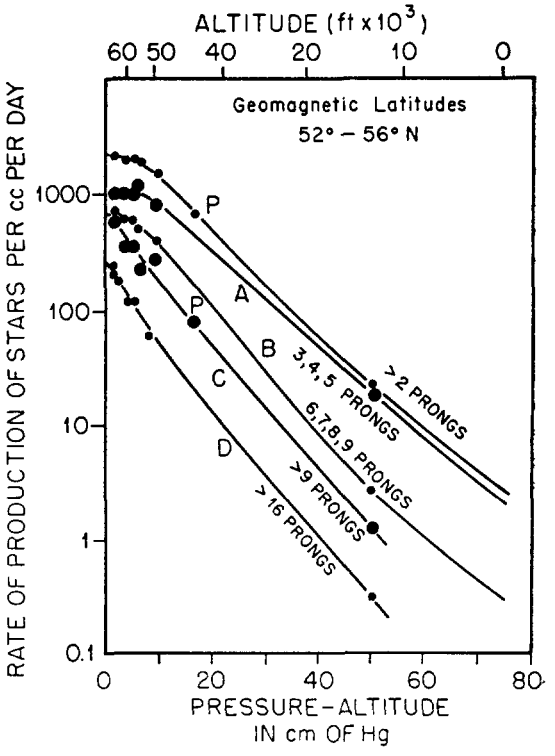

FIG. 7. Rate of production of nuclear disintegrations in photographic emulsion, as a function of altitude at 54°N (from LORD, Ref. (14)).

SOLAR COSMIC RADIATION AT SST ALTITUDES

21. Although abundant data are available on the fluxes and energy spectra of solar flare

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protons in free space, information is scarce on residual fluxes and spectra at SST altitudes. More-detailed data at "balloon" altitudes (i.e. 95,000–120,000 ft) indicate that an extremely rapid transition occurs as a beam of solar protons enters the atmosphere, the bulk of such protons having only limited penetrating power. This extremely steep transition makes extrapolations from "balloon" altitudes to SST altitudes virtually impossible.

22. A direct dose-estimate is available from a balloon-borne ionization chamber which ascended through the SST altitude region during the maximum of the flare event of 16 July, 1959, which was unusually intense. The recordings were interpreted to indicate a dose rate of 2 mrad/hr for a tissue phantom or human target at 80,000 ft.[15]

23. Theoretical analysis of the transition of solar protons in the atmosphere[16–18] is useful only for rough estimates. At SST altitudes there is so much shielding from the 28–74 g/cm^2 of overlying atmosphere superimposed on the local shielding system of the vehicle that the radiation reaching the SST represents only a small fraction of the extra-atmospheric flux. For this reason, minor errors in measurement of the extra-atmospheric energy spectrum are greatly magnified in dose extrapolations.

24. Further inaccuracy in the estimation of residual fluxes and energy spectra in the atmosphere may result from difficulties in assessing the attenuation of high-energy protons in matter.[19,20] Two different interaction mechanisms account for this attenuation: ionization and nuclear collision. The former is a strictly local process, involving short-range secondaries, and can be treated theoretically for a given spectrum with any desired accuracy in the assessment of absorption and depth dose distribution. The latter, however, involves the production of multiple generations of secondaries, some of considerable range, and it defies accurate theoretical treatment. In the energy range up to about 200 MeV, ionization is the predominant attenuation process, but neutron production is also present and may dominate the dose at SST altitudes. In fact, theoretical analysis shows that neutrons may contribute a large part of the dose at SST altitudes from most solar events, since the incident protons of low energy which are absorbed higher in the atmosphere through nuclear collisions[21] can produce neutrons which penetrate to SST altitudes (see para. 29).

25. Only on rare occasions (seven times in the past two solar maxima, i.e. in the last 20 yr) have flares occurred that carried substantial fluxes of 1.0 GeV energy and above. These giant flares have been accompanied by geophysical phenomena which could have provided a basis for their detection early enough to have enabled an SST to be rerouted or to descend to a lower altitude.

26. The flux and energy spectrum of a flare-produced particle beam arriving at the earth change continuously as the event progresses. Depending on the conditions of the interplanetary magnetic field, a more or less steeply increasing flux of high-energy particles arrives first, followed by large but gradually declining fluxes of medium- and low-energy particles (see para. 7). For a maximum flare of the ordinary, nonrelativistic type,[22] a theoretical estimate of the depth-dose distribution from the primary radiation in a 30-cm diameter tissue sphere at SST altitudes is shown in Fig. 8; however, the data in Fig. 8 are based on the outer envelope of the entire family of energy spectra, with the result that they show maximum dose rates and maximum depth of penetration, which will not actually occur simultaneously. This accounts for the apparent discrepancy between the values in Fig. 8 and the measurement cited in para. 22. With increasing penetration of the primary and secondary radiations into the atmosphere, their spectra and LET distribution undergo changes which may be calculated to increase the overall QF of the radiations (see para. 31 *et seq.*) from a value of about 2.2 at 90,000 ft to about 3.5 at 55,000 ft.

27. The giant flare of 23 February, 1956, by far the biggest of the seven exceptionally large events of the last 20 yr, carried enormous particle fluxes in the energy region of several hundred MeV and large fluxes extending well above 1 GeV. As a result, it has been reported to have caused increased radiation intensities down into the atmosphere as far as present jet transport altitudes.[23] Early estimates[13,15] of the prompt proton spectrum from this event are substantially higher, however, than recent estimates

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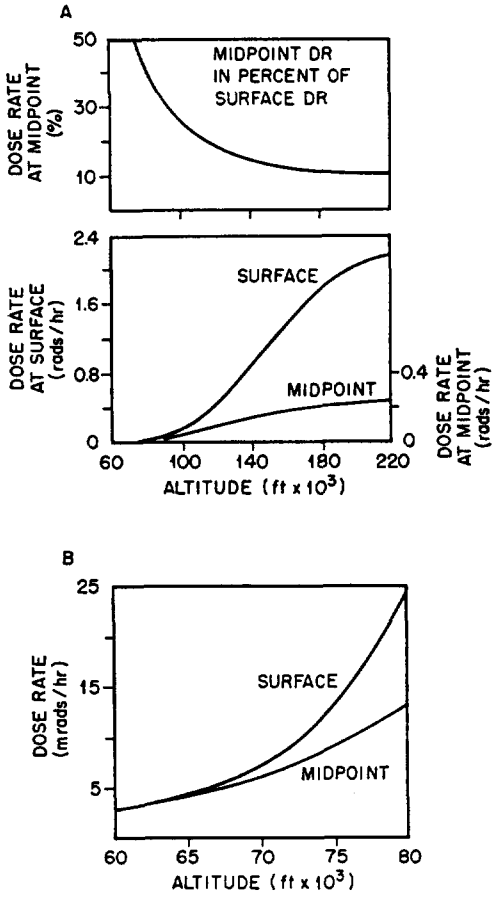

FIG. 8. Surface and midpoint exposure rates in 30-cm diameter tissue sphere behind 1 g/cm² shielding for primary radiation from a typical flare-produced proton beam in the atmosphere (from SCHAEFER, Ref. (17)).

based on an incident spectrum more consistent with the neutron monitor and ionospheric absorption (riometer) data. The latter indicate a maximum dose of 1–2 rad during the first hour of the event at 60,000–80,000 ft in the polar region (Table 3).

Relation to latitude

28. Although the geomagnetic cutoff mechanism affects flare-produced particles as well as galactic cosmic rays, cutoff energies are reduced during magnetic storms to the extent that low-energy particles may have access at such times to normally forbidden latitudes. However, since magnetic storms are produced by the slowly moving plasma ejected from flares, they do not develop until 24–36 hr after the onset of the flare, at which time the maximum of the flare-produced radiation surge is usually over. Nevertheless, flare events may occasionally follow one another at intervals of a few days, so that the storm of one flare may reach the earth just at the time when the maximum particle flux of the succeeding event arrives. When this happens, the geomagnetic cutoff energies are greatly reduced, from the geomagnetic poles down to at least 50° geomagnetic latitude.

Neutron component

29. The transition of solar particle fluxes in the atmosphere is not well measured, but the neutron component has been calculated on the same basis as the neutron component induced by galactic cosmic rays. FLAMM and LINGENFELTER[21] have analyzed the production of neutrons by the two solar flares of 12 and 15 November 1960, with particular attention to altitudes of 50,000–80,000 ft. The flares were typical large flares. From the proton spectra given by FREIER and WEBBER,[26] they have calculated instantaneous dose rates from primary and secondary protons and from neutrons as a function of atmospheric depth and P_0. During each flare, the rigidity parameter P_0 was observed to change with time, and neutron dose rates between 0.01 and 0.1 rad/hr (1–30 per cent of the proton primary plus secondary dose rates) were estimated to last for almost a day. From these data, it may be calculated that neutrons of 0.1–10 MeV contribute the bulk of the neutron dose-equivalent (Fig. 9), the LET distribution of the spectrum corresponding to an overall QF (see para. 31 *et seq.*) of 8.5 at a depth of 3 mm in tissue.

30. It is noteworthy that during the February 1956 flare the sea-level neutron intensity at northern latitudes increased to forty-five times its normal value,[27] whereas the total ionization at sea level increased only to about three times normal.[28] The contribution of the neutron component to the total ionization in air at sea level was probably small. Therefore, the relatively high hydrogen content of tissue conceivably could magnify the flare-produced additional ionization dosage in view of the high

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Table 3. Maximum hourly dose rates at the geomagnetic poles during the giant flare of 23 February 1956, in relation to altitude

Altitude (ft)	Dose rate (rad/hr)		
	Present estimates		Earlier estimates
	Maximum primary plus secondary radiation*	Assuming no nuclear collisions†	Primary radiation alone
60,000	0.36	0.15–0.8	2.5‡
70,000	0.57		6.2‡
75,000	0.68	0.4–2.0	4§
80,000	0.80	0.6–2.5	16‡

* Data of CURTIS.[24]
† Data of FOELSCHE.[25]
‡ Data of FOWLER and PERKINS[13] for average dose over first hr.
§ Data of FOELSCHE and GRAUL.[16]

neutron intensity. This would entail a further increase of the corresponding dose equivalent. Any extrapolation as to the corresponding conditions at SST altitudes is subject to a large margin of uncertainty.

QF VALUES FOR COSMIC RAYS

General considerations

31. The Report of the ICRP Committee on RBE[29] emphasized that RBE is a term for describing the result of experimental comparisons between the effects of different radiations. It proposed that in considerations of radiation protection, QF should be the factor "which ensures that the risk from a maximum permissible dose of high-LET radiation never exceeds that from a maximum permissible dose of the low-LET reference radiation" (para. 23 in Ref. (29)). This distinction between RBE and QF is accepted in this report, and the experimental facts, theoretical principles, and conclusions of the RBE Committee are the basis of what follows. Experimental information is cited only when it is too recent to have been available to the RBE Committee, and extended discussion is confined to problems which that Committee did not consider in detail (para. 102 in Ref. (29)) and to implications of newly available experimental information on genetic effects.

32. The RBE Committee laid down that for protection purposes the dose equivalent (DE), which is expressed in rem, is the product of absorbed dose D (in rad), quality factor QF,

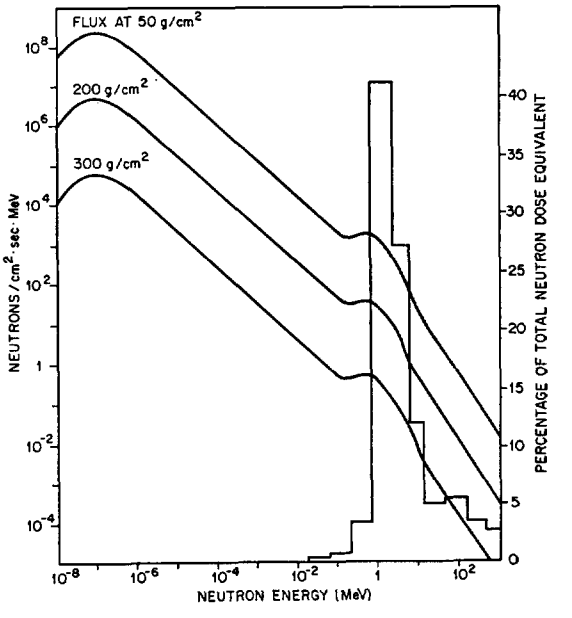

FIG. 9. Combined solar neutron energy spectrum (from FLAMM and LINGENFELTER, Ref. (21)) with the distribution of the dose equivalent at 50 g/cm² atmospheric pressure (about 70,000 ft altitude) calculated as in Fig. 6.

dose distribution factor DF, and other necessary modifying factors,

$$(DE) = D(QF)\ (DF) \ldots\ldots$$

Where LET varies along a particle track, DE must be assessed by some method of integration

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over segments of track length with the use of the appropriate QF for the LET concerned. The values for QF recommended by the RBE Committee are given in Table 4.

Table 4. The relationship between QF *and* LET*

LET (keV/μ in water)	QF
3.5 or less	1
3.5–7.0	1–2
7.0–23	2–5
23–53	5–10
53–175	10–20

* From ICRP Committee on RBE.[29]

33. Table 4 covers LET values for electrons and protons of all possible energies; however, for high-energy particles of greater mass, including those which may be produced by nuclear interactions of high-energy protons in tissue, the LET may be greater than the upper limit given in this table.

34. The QF values given in the table are to be used not only for maximum permissible exposures, but also for "accidental high exposures" (25 rem once in a lifetime) and for "emergency exposures" (planned on the basis that the individual will not receive a dose in excess of 12 rem) (para. 88–91 in Ref. (29)). If it is accepted that the known dose-rate dependence of effects of exposures to low-LET radiations may be ignored in this application, the principle is clearly equally acceptable for effects of high-LET radiations which show a lesser dependence on dose-rate.

35. QF factors are not appropriate for use in evaluating the severity of injury in case of acute exposure to high doses (para. 92–101 in Ref. (29)); however, such exposures are not expected to occur under the conditions of interest in this report.

36. In most practical situations the amount of high-LET radiation is but a small fraction of the total, and in these circumstances it is conservative if too high a value for QF is used, since QF is the factor which ensures that the risk from high-LET radiation does not exceed that for low-LET radiation. In certain situations, however, the high-LET radiation may be a larger fraction of the total, and it may then be important to use as exact a value for QF as possible. Nevertheless, there is no adequate basis at present to justify any changes in the accepted QF for high-LET radiation when considering the problems in normal protection work.

Somatic effects

37. The RBE Committee surveyed data available in 1962 and noted that "the extent of the data on RBE relevant to low dose and low dose-rate conditions is very small indeed" (Summary in Ref. (29)). This summing-up still stands 2 yr later. Newly available data on high-energy radiations[30] agree with earlier reports in giving RBE values of $\sim$1 for lethal and other acute effects in large animals exposed at high dose rates to neutrons or to protons and of $\sim$10 or less for delayed effects of neutrons in mice and rats, such as tumor induction (gamma rays the reference radiation). Experiments with mono-energetic neutrons on the lens[31] and testis[32] of the mouse are in agreement with earlier work on the spleen and thymus, in finding that the RBE decreases with increasing neutron energy above 0.4 MeV. A survey of experimental work of various other kinds, likewise, leads to the conclusion that the RBE of neutrons decreases with increasing energy.[33] In work with mammals, there is still no example of a somatic effect with an RBE comparable in magnitude to the limiting values at low dose rates deduced for chromosome aberrations in plant cells. Thus the new information, even if small in extent, provides additional support for the general conclusions of the RBE Committee embodied in Table 4.

38. There is little information on the effects of high-LET particles, including those which may result from nuclear interactions of high-energy radiation with the nucleons of tissue or of the immediate environment of the body. A number of experiments with cultures of mammalian and other cells have shown, as expected, a decreasing efficiency per rad with increasing LET once the LET has exceeded a certain value. Theoretically, the same general result might be expected for any biological effect that depends on survival of cells: too large a local deposition of energy would either waste radiation

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or kill the cell, in either case leading to a decrease in RBE with increasing LET above a certain level of LET.

39. In cell culture experiments, the maximal observed RBE corresponds to an LET of 100–300 keV/μ, a region of LET which is in part outside the highest values considered in Table 4. There is no direct experimental evidence in mammals on RBE values for LET's in this region, yet some value must be assumed in order to deduce the dose equivalent for exposure to high-energy protons, for example, and thus to their high-LET nuclear collision recoil secondaries. Since, in practice, exposure of the tissues of man to high-energy radiations is seldom, if ever, to a mono-energetic flux but rather to a wide range of energies, and since the RBE decreases above as well as below the LET for maximal RBE there will be a safety factor in assuming a maximum and constant value for QF at and above LET's of a certain value. Until more information becomes available, it is recommended that this QF be 20 and that it should be taken to apply at all LET's greater than those mentioned in Table 4.

40. The cell culture experiments already referred to were not designed to reveal the biological effects of those nuclear interactions which result in the simultaneous production of several particles of high LET. Such "stars" lead to a very high local absorption of energy and for the reasons mentioned earlier are not likely therefore to have an unusually high RBE. Although no direct experimental information is available on the biological effects of "stars," it is reasonable to conclude that they do not represent a special kind of hazard and do not require specific consideration when setting limits to high-energy exposure.

41. There is one way, however, in which a qualitatively new kind of biological effect might conceivably be produced by high-LET particles more massive than a proton (para. 104 in Ref. (29)). At maximal LET, a proton has a residual path-length in tissue comparable to the dimensions of a single cell, whereas a heavier particle with the same LET has a longer path-length and may therefore affect a track of tissue up to many cells in length. Such tracks of affected cells have been observed experimentally in the skin of mice exposed to cosmic radiation in the upper atmosphere[34,35] and, although of little functional importance in the skin, might be of much greater importance in the embryo or in vital organs such as the brain. Attempts to study this question with microbeam irradiation[35,36] suggest that the observed changes per exposed cell are smaller than for the same number of ions per cell delivered to a larger volume of tissue; however, no RBE value can be cited for an effect that is produced by high-LET radiation but not by low-LET radiation under the conditions of interest. Some other means will have to be found, therefore, if such effects are to be taken into account in calculation of the dose equivalent. Apart from this special case, the risk-limiting somatic effects from high-energy radiations are not different from those ordinarily considered in protection work.

Genetic effects

42. For present purposes, special interest centers on the choice of QF values appropriate for mutation induction by high-LET radiation. The conclusions of the RBE Committee were that the premeiotic stages in male germ cells (spermatogonia) and later meiotic stages in female germ cells (early oocytes) are the stages most at risk, and that the mutagenic efficiency of low-LET radiation for specific locus mutations in the mouse shows a dose-rate effect. The experimentally determined RBE's for comparisons between high- and low-LET radiation were all derived from short exposures at high dose-rates. The values were less, or much less, than the QF values in Table 4, but since there are good experimental and theoretical reasons to expect that the RBE for high- as compared with low-LET radiations will increase (up to some limit) with decreasing dose rate, the QF values in the table were taken to be appropriate for protection purposes.[29]

43. In 1963, when the RBE Committee reported, there was no experimental information about RBE for the yield of mutations from protracted exposures, the type of exposure and effect which they considered the most important from the point of view of protection recommendations (para. 73 in Ref. (29)). Recently, the first results of two such investigations in male mice have been reported, high-LET radiation being represented by fission neutrons

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and low-LET radiation by gamma radiation.[37,38] The experimental RBE values were 30 and 18, respectively. It is not yet known if the values obtained in experiments like this involving no more than 3 months' exposure at dose rates of ~0.1 rad/hr, or greater, approximate the limiting value appropriate for protection purposes. Although the reported values are preliminary and have wide confidence limits, it must be accepted that an RBE of 20–30 for irradiation of mouse spermatogonia is higher than other RBE's for genetic effects considered by the RBE Committee. These observed values do not differ greatly, however, from the RBE for acute effects on eye-color mutations in the wasp *Mormoniella*.[39]

44. As an interim measure, until more is known, it is recommended that the QF values of Table 4 continue to be used for protection purposes when considering genetic effects. The contribution of high-LET radiation to the genetically significant dose to the population is so small that quite considerable variations in QF make little difference.

45. There is a special genetic problem relating to occupational exposures to radiation. Such exposures, as in a high-flying aircraft or near a high-energy particle accelerator, are in practice intermittent rather than continuous and involve adults, mostly males, at an age when they are conceiving children. Thus the genetic risk from such exposures is not entirely the consequence of irradiation of spermatogonia during the previous years of life, the situation usually envisaged when considering genetic risks following exposure of males in the general population, but it includes possible damage induced in germ cells during the sensitive post-meiotic stages. The number of individuals likely to be involved is small, and the genetic problem is one of possible deleterious effects in the offspring they conceive shortly after irradiation. Hence, this particular aspect of the genetic problem is of relatively lesser importance than those aspects related to spermatogonial injury.

46. Studies on the induction of dominant lethal mutations in mouse spermatozoa indicate that fast neutrons give essentially the same yield at widely different dose rates, with an RBE of about 6.0 when compared with X-radiation at high dose rates (see Ref. (40)). The RBE for dominant lethal induction in spermatids was somewhat higher than in spermatozoa.[40] For the induction of specific locus mutations in postspermatogonial germ cells of the mouse, the RBE of fission neutrons has been reported to be about 5.0, irrespective of dose rate, with no evidence of dose rate-dependent variations in the effectiveness of either the neutron- or gamma-radiations.[41] No values of the RBE for chromosomal translocations in germ cells seems to be available. The experimental information is therefore scanty but compatible with the QF values given in Table 4. It may be concluded on the basis of present knowledge that this table is a satisfactory basis for assessing the genetic risk, both to individuals and to the population, of occupational exposures to high-LET radiation.

47. For LET's higher than the values associated with neutrons of ~1 MeV there is no information to draw on. The unexpected results with gene mutations in mouse spermatogonia exposed to fission neutrons complicate the interpretation of experiments with high-LET radiation on other kinds of mutation and other forms of life. As in the case of cellular damage, and for similar reasons, it is to be expected that the RBE will be maximal at a certain LET and will decrease at higher LET's, but there is no quantitative information about the LET at which this occurs or about the value of the maximal RBE. For reasons of consistency and because the QF values in Table 4 are held to apply for genetic as well as for somatic effects,[29] it is recommended that QF for genetic effects be taken as 20 for LET values greater than those specified in the table.

48. High-LET radiation, which may be of special somatic interest because of track formation (see para. 41), will probably not have any correspondingly unusual genetic effects. Hence, "stars" are not to be considered a special genetic hazard.

MAGNITUDE OF CUMULATIVE EXPOSURE TO AIR CREW

Age and sex of crew

49. Because of the requirement for extensive flying experience, pilots and operators of the SST will be predominantly, if not exclusively, 30 to 60-year-old males. The probable age of

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the pilots can be predicted from the fact that many airline jet pilots are in their fifties. A study of senior airline pilots (age range 45–59 yr) showed no evidence of premature deterioration or any predilection to particular disease in this group. The U.S. airlines and the Federal Aviation Agency have recognized this, setting an arbitrary time limit for retirement at 60 years of age.[42]

50. Members of the passenger-compartment crew, approximately equal in number to the operating crew, presumably will be predominantly females, as in present aircraft. Estimation of the age of stewardesses is far less certain, but the average age will probably be in the 20 to 30 yr range. The average duration of crew duty will also be considerably shorter in females than in males, and estimates of 5–10 yr or less are suggested, as compared to 20–30 yr maximum flying time for males.

Work schedule

51. Whether, in view of shorter flight times, the work schedule of the crew of the SST will be treated with the same approach as that of the subsonic jet, or whether an 8-hr day or major fraction thereof will constitute a "duty-day," is not known. If an SST flight occupies so short a time that ground turn-around time and the return flight can be accomplished within a 6 to 8-hr period, it may be decided to use the same crew for round trip flights. Such a schedule might have special significance in relation to flares.

52. Flight profiles will be important in determining the duration of high-altitude exposure, but it cannot be predicted reliably what proportion of any given flight will occur at cruising altitudes.

53. The hourly radiation dose to occupants of the SST may be estimated as the sum of the contributions from solar radiations and galactic radiations, including neutrons (Table 5). It is noteworthy, however, that the hourly values tabulated for solar flares are not comparable to those for galactic radiations in that they represent exposure from discontinuous events averaged over an interval of years. Consequently, they do not really denote dose rates but rather dose rate commitments at the different altitudes. From the values in Table 5, it may be seen that the estimated maximum dose rate commitment ranges from about 1.2 mrem/hr at 60,000 ft to 3.0 mrem/hr at 80,000 ft.

54. If an SST were to fly a polar route of 4000 miles at an average speed of Mach 2 and at an altitude of 60,000–80,000 ft throughout, the resulting cosmic ray dose to occupants of the plane would total 3–6 mrem, provided that exposure to solar flares were avoided. Even if an annual crew exposure of 500 hr at these altitudes were assumed, an individual crew member would be unlikely to receive more than 2 rem/yr, which can be compared with the Commission's recommended maximum permissible dose of an average of 5 rem/yr for radiation workers.[43]

MAGNITUDE OF CUMULATIVE EXPOSURE TO PASSENGERS

Number of passengers

55. During 1964, approximately 3.5×10^6 passengers were carried on North Atlantic routes by the eighteen member airlines of the International Air Transport Association, an increase of 25 per cent over the corresponding number of passengers for 1963 (*New York Times*, 1 Feb. 1965, p. 37M). Data for preceding years (Fig. 11) indicate a comparable rate of increase annually since 1948. Based on the growth rate of U.S. air traffic (see Table 6), the Federal Aviation Agency has forecast an increase of 30×10^9 U.S. airline passenger miles by mid-1970 or early 1971, with an increase in the number of jet transports to about 1085, as compared with the 432 jets in operation during 1964 (*New York Times*, 2, Feb. 1965, p. 54M).

56. What fraction of the total passenger traffic will eventually be borne by SST aircraft would seem at first to be limited more by the numbers of such aircraft available and the routes over which they can feasibly be used than by passenger demand. Ten 200-passenger SST's flying 1000 hr/yr each at 2000 mph could provide a total of 4×10^9 passenger-miles per year (about 7 per cent of the 1963 total domestic U.S. passenger-miles). Although such a sustained aircraft utilization may not be realistic, the yearly number of SST passengers to be expected may well exceed 10^7 within the next decade.

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Table 5. Radiation exposure to occupants of SST in relation to altitude (values are for polar latitudes)

Radiation	Altitude (feet) 30,000	40,000	50,000	60,000	70,000	80,000
Galactic (maximum)						
Charged particles and gamma rays						
(mrad/hr) *	0.14	0.30	0.47	0.64	0.77	0.86
(mrem/hr) †	0.24	0.44	0.67	0.95	1.2	1.6
Neutrons						
(mrad/hr) ‡	0.006	0.009	0.015	0.017	0.022	0.032
(mrem/hr) §	0.048	0.075	0.116	0.134	0.172	0.254
Total						
(mrad/hr)	0.15	0.31	0.49	0.66	0.79	0.89
(mrem/hr)	0.29	0.52	0.79	1.08	1.37	1.85
Solar (avg.)						
(mrad/hr) ‖	0.001	0.004	0.014	0.045	0.15	0.45
(mrem/hr) ¶	0.005	0.019	0.051	0.150	0.43	1.25
Total (galactic plus solar)						
(mrad/hr)	0.15	0.31	0.50	0.70	0.81	1.34
(mrem/hr)	0.29	0.54	0.84	1.23	1.80	3.10

* From Fig. 4; values for quiet sun (1954).
† From Fig. 10; values for quiet sun (1954).
‡ From Table 1.
§ From Table 1; with QF = 8 (see para. 13).
‖ From Fig. 4; values are based on the sum of all discontinuous flares during 1952–1960, except the giant flare of 23 February 1956, averaged over the entire period; thus they do not actually denote dose rates to individuals but rather dose rate commitments to hypothetical populations exposed at the different altitudes.
¶ QF = 3.5–2.2 at 55,000–90,000 ft, extrapolated to a value of 5 at 30,000 ft (see para. 26).

Age and sex of passengers

57. Data on the age and sex of eastbound transatlantic air passengers leaving New York in April–September 1963 indicate greater relative numbers of adults and males, and decidedly few children, in the passenger group than in the general population (Table 7). Information concerning the proportion of pregnant women among passengers is not available.

58. The genetically significant dose for passengers is presumably somewhat less than it would be for a random sample of the general population similarly exposed, because of the aforementioned difference in age distribution. The extent of the difference is unlikely to exceed the factor by which children and young adults are under-represented among the passengers, i.e. it should not exceed twofold, or at the very most threefold, and will in all probability be of less importance than this. The reasoning follows from the observations that the age group 19 and under, which accounts for 39 per cent of the general population, is represented by less than 15 per cent of the passengers (Table 7). Better information on the age distribution for passengers would be required if an attempt were to be made to refine this estimate.

Radiation doses

59. The dose rate factors (Table 5) for the crew are equally applicable to the passengers, although the total cumulative exposure per passenger will be far less. On the other hand, because there are so many more passengers than crew members, the protection criteria for the general population, rather than those for occupational groups, should be applied to the passengers.

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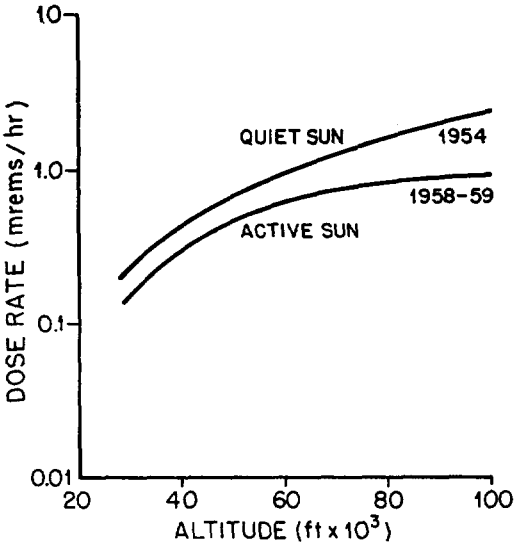

FIG. 10. Dose rate (in rem) of galactic radiation at polar latitudes in relation to altitude. The curves were derived from those shown in Fig. 4 by means of the QF values given in Table 4 (from FOWLER and PERKINS, Ref (13)).

60. Most passengers may be expected to make no more than one or two round-trip flights per year, and none will accumulate as many flight-hours as will crew members. If one assumes an average of 12 flight-hr/y per passenger (four of the polar flights mentioned in para. 54), with the entire flight time being spent at 80,000 ft and if exposure to major solar flares is avoided, then the average exposure per passenger per year will not exceed 30 mrem. This may be compared with the Commission's recommended maximum permissible dose of 500 mrem/yr for individual members of the public.[43]

Table 6. *U.S. airlines passenger traffic* 1962–1964

Year	Number of passengers	Number of passenger-miles
1962*	61×10^6§	43.7×10^9
1963†	72×10^6	53×10^9
1964‡	82×10^6	59×10^9

* From *World Almanac* 1964, *New York World-Telegram*, New York, 1964, p. 765.

† From *Aviation Week*, Thirty-first Inventory of Aerospace Power, Special Issue, March, 1964, p. 164.

‡ Estimate from Air Transport Association, cited in *U.S. News and World Report*, vol. 58/1, 4 Jan. 1965, p. 80.

§ Includes 54.3×10^6 domestic and 6.6×10^6 international passengers.

61. In addition to the exposure of individual crew members and passengers, there is the dose to the whole population to be considered. The

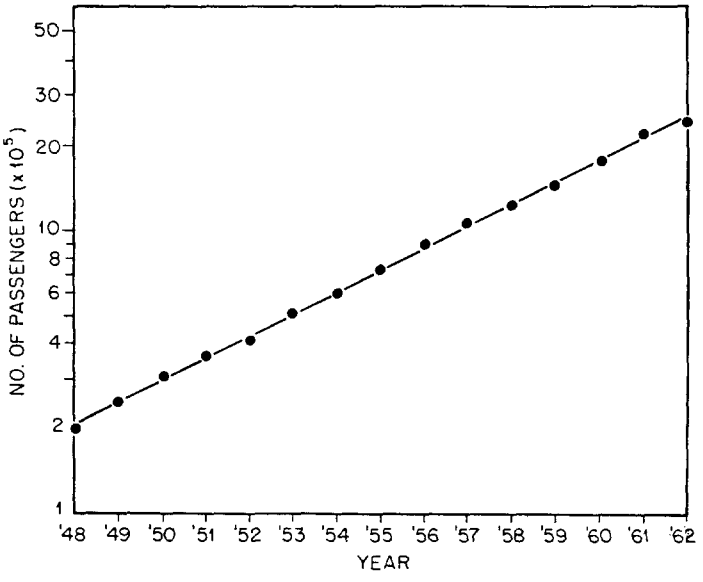

FIG. 11. Air passengers traveling between the U.S. and Europe, in relation to year, 1948–1962.[44]

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Table 7. Age and sex distribution of eastbound transatlantic passengers, as compared with the population of the U.S.

Age (yr)	Passengers*		U.S. population†	
	Male (%)	Female (%)	Male (%)	Female (%)
under 12	5.9		25.3	
12–19	3.7	5.5	7.0	6.8
20–34	14.0	14.0	9.2	9.3
35–64	28.1	21.4	16.2	16.9
over 65	3.7	3.7	4.1	5.2

* Total passengers: 610,000. Between April and September, 1963, approximately 610,000 eastbound transatlantic passengers were estimated to travel on flights leaving New York.[45]

† Total population: 186,591,000 (based on U.S. Census, 1963).

fraction of the population likely to be carried as SST passengers cannot be estimated precisely, but probably will not exceed 1 per cent within the foreseeable future (see para. 56). On this basis, the genetic dose to the population would not be expected to be greater than 0.3 mrem/y, or 0.01 rem/generation. This may be compared with the Commission's recommended maximum permissible dose of 5 rem/generation,[43] although it is noteworthy that the latter applies to the total dose from all man-made sources of radiation other than medical exposures.

SUMMARY AND CONCLUSIONS

1. The radiobiological aspects of the SST have been reviewed, with reference to conditions at altitudes of 60,000–80,000 ft.

2. Radiation at these altitudes falls into two categories: (1) that attributable to galactic cosmic rays and (2) that attributable to solar flares.

3. Galactic cosmic radiation varies with geomagnetic latitude, as well as with altitude, being maximal in the polar regions. It varies inversely in relation to solar activity. At altitudes up to 80,000 ft, it contains few heavily-ionizing primary particles and is composed chiefly of secondaries with comparatively low QF. Under pessimistic assumptions, radiation from this source is estimated not to exceed 1–2 mrem/hr at altitudes up to 80,000 ft.

4. Solar-flare radiations are produced intermittently in outbursts associated with sun-spots. These outbursts are brief, highly variable in intensity, and not predictable except in a general way. As in the case of galactic cosmic rays, the solar radiations increase in intensity with geomagnetic latitude as well as with altitude. At altitudes up to 80,000 ft solar radiations, which are composed of protons and secondaries, may be expected to contribute on the average only a small fraction of the total exposure to occupants of the SST. On rare occasions, however, perhaps once or twice during an 11-yr period, a giant relativistic particle event may be expected to deliver a dose equivalent at peak rates of as much as 1–10 rem/hr at an altitude of 80,000 ft on polar flights, with 0.5–5 rem or more in the first hr and decreasing amounts in the succeeding 12–48 hr. Hence, measures are called for which can detect such events in time to warn the SST to descend to a lower altitude if necessary.

5. If exposure to major solar flares can be avoided, the cumulative exposure of crew and passengers to solar, as well as to galactic, cosmic radiations should be within permissible limits. For example, the estimated maximum dose from galactic radiations at 80,000 ft is not more than four times that at 40,000 ft. Hence, the dose received per mile flown in a Mach 3 SST at 60,000–80,000 ft should not greatly exceed that received in a subsonic jet at 35,000–40,000 ft.

6. There are uncertainties, however, in the foregoing considerations, which call for further research on the following questions.

(a) *The biological effects of energetic heavy nuclei on cells and tissues* (see para. 41).

(b) *The relative biological effectiveness of high-LET radiations at low dose rates* (see para. 37 and

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43). For the present, the values of QF as recommended by ICRP should be used, with the addition that a QF of 20 be taken for radiation of LET exceeding the range now covered.

(c) *The development of practical methods to enable the early detection and avoidance of solar flare radiation by the SST.*

(d) *The variation in quantity and quality of cosmic radiations (including primary heavy nuclei) at SST altitudes, as influenced by latitude, altitude, solar activity, and shielding.* (It cannot now be accurately predicted how the attenuation of cosmic rays and production of secondaries by the materials of the aircraft will affect the dose equivalent to occupants of the SST.) It is recommended particularly that an experimental program be initiated for measuring the neutron spectrum as a function of latitude at present jet plane and SST altitudes. These measurements should be made annually for the next several years, at least until after the peak of the next solar cycle, in 1968–1969. At that time, measurements should be made during large flares, mainly at high latitudes, although the range of the routine measurements should extend between geomagnetic latitudes 20 and 70 (for a similar recommendation of systematic measurement of flare radiations in reference to the SST, see WILSON, Ref. (1)).

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