38. M. Koepcke, *Mem. Mus. Hist. Nat. Javier Prado* **3**, 1 (1954); *Bonner Zool. Beitr.* **9**, 130 (1958); H.-W. Koepcke, *Bonn. Geogr. Abh.* **29**, 1 (1961).
39. B. Vuilleumier, unpublished data.
40. F. Vuilleumier and B. Vuilleumier, unpublished data.
41. C. C. Caldenius, *Geogr. An.* **14**, 1 (1932); E. Feruglio, *Descripción Geológica de la Patagonia* (Dirección General de Yacimientos Petrolíferos Fiscales, Buenos Aires, 1949), vol. 2; R. F. Flint, *Holmbergia* **6**, 87 (1959); ——— and F. Fidalgo, *Bol. Dir. Nac. Geol. Min. Argentina* **93**, 1 (1963); *Bol. Inst. Nac. Geol. Min. Min. Econ. Trab.* **119**, 1 (1968); J. Frenguelli, *GAEA* **2**, **117** (1957); J. Polanski, *Geol. Soc. Amer. Spec. Pap.* **84**, 453 (1965).
42. V. Auer, *Ann. Acad. Sci. Fenn. Ser. A3* **50**, 1 (1956); W. Czajka, *Quaternaria* **15**, 245 (1966); P. Groeber, *Rev. Mus. Mar del Plata* **1**, 79 (1952).
43. J. G. Andersson, *J. Geol.* **14**, 91 (1906); C. M. Clapperton, *J. Glaciol.* **10**, 121 (1971).
44. F. Ahlfeld and L. Branisa, *Geología de Bolivia* (Instituto Boliviano de Petroleo, La Paz, 1960); G. Steinmann, *Geología del Perú* (Winters, Heidelberg, 1930); J. Tricart, *J. Glaciol.* **5**, 857 (1965).
45. S. Hastenrath, *J. Glaciol.* **6**, 541 (1967).
46. R. F. Flint, *Geogr. Rev.* **53**, 123 (1963).
47. H. Kinzl, in *Geo-Ecology of the Mountainous Regions of the Tropical Americas*, C. Troll, Ed. (Geographisches Institut, University of Bonn, Bonn, Germany, 1968), pp. 77–90).
48. A. Kessler, *Erdkunde* **17**, 165 (1963).
49. C. Emiliani, *Bull. Geol. Soc. Amer.* **75**, 129 (1964); *Science* **154**, 851 (1966).
50. P. Groeber, *Holmbergia* **1**, 71 (1936).
51. H. Ebert, *An. Acad. Brasil. Cienc.* **32**, 51 (1960); H. Mortensen, *Z. Geomorphol.* (Neue Folge) **1**, 296 (1957).
52. M. Teruggi, *J. Sediment. Petrol.* **27**, 322 (1957).
53. A. Castellanos, in *Proc. IV Int. Congr. Int. Assoc. Quaternary Res.* (1953), p. 1.
54. I. Bowman, *The Andes of Southern Perú* (Holt, New York, 1916).
55. C. N. Fenner, *Bull. Geol. Soc. Amer.* **59**, 895 (1948).
56. H. F. Garner, *ibid.* **70**, 1327 (1959); *Sci. Amer.* **216**, 84 (April 1967).
57. E. P. Lanning, *Sci. Amer.* **13**, 68 (1965).
58. J. P. Bakker, *Z. Geomorphol.* **1** (Suppl.), 69 (1960); J. J. Bigarella and G. D. de Andrade, *Geol. Soc. Amer. Spec. Pap.* **84**, 433 (1965); J. J. Bigarella and M. R. Mousinho, *Z. Geomorphol.* (Neue Folge) **10**, 150 (1966); ———, J. X. da Silva, *Processes and Environments of the Brasilian Quaternary* (University of Paraná, Curitiba, Brazil, 1965); J. Dresch, *Quaternaria* **8**, 205 (1966); J. M. Mabesoone, *Z. Geomorphol.* (Neue Folge) **10**, 419 (1966); in *Atas Simpós Biota Amazônica* **1**, 327 (1967).
59. J. J. Groot and C. R. Groot, *Mar. Geol.* **4**, 525 (1966); D. B. Ericson, M. Ewing, G. Wollin, *Science* **146**, 723 (1964).
60. A. N. Ab'Saber, *Atas Simpós Biota Amazônica* **1**, 35 (1967).
61. I especially thank J. Haffer for innumerable suggestions and advice. I also appreciate the comments of O. Solbrig and F. Vuilleumier.

Radiation Exposure in Air Travel

Levels of ionizing radiation at high altitudes do not significantly increase the population dose.

Hermann J. Schaefer

The prospect of present-day, large-scale passenger operations shifting from jet aircraft, flying at subsonic speed and at altitudes in the region of 25,000 to 40,000 feet (approximately 7.6 to 12.2 kilometers), to supersonic transports (SST), flying at two to three times the speed of sound and at altitudes of 60,000 to 65,000 feet, has raised the question of what harmful effects the substantially higher levels of environmental radiation could have on crew members and passengers. In connection with these developments, an evaluation and comparison of the environmental radiation levels at conventional jet and at SST altitudes appears necessary.

The author is head of the biophysics division at the Naval Aerospace Medical Research Laboratory in Pensacola, Florida 32512, and conducts operational and experimental radiation monitoring on high altitude flights and space missions. Opinions stated in this article are exclusively those of the author and do not necessarily reflect the view of the Navy Department.

Solar Proton Beams

In discussions of radiation hazards at high altitudes, interest usually centers on solar particle beams produced by flares. Inevitably, the giant solar flare of 23 February 1956 is cited as an event that is estimated to have created, during the first hour, radiation levels well in excess of 100 millirems per hour at an altitude as low as 35,000 feet. At that time, commercial passenger jets were in all likelihood at an altitude that exposed passengers to radiation levels which, in terrestrial installations, would have called for a number of precautionary measures. It must be pointed out, however, that forecasting solar flares has become a routine matter and is now conducted continuously, with a global network of observation stations. It is therefore extremely unlikely that an SST could continue at cruising altitude without knowing that a major flare was in progress, even if its radiation monitoring instruments were malfunctioning.

The hazard that solar flares create for high-flying aircraft is further alleviated by the infrequent occurrence of the kind of flare that would produce a substantial increase in the level of galactic radiation at an altitude of only 65,000 feet. During solar cycle 19, which lasted from 1954 to 1965, seven such flares occurred. During the smaller maximum of cycle 20, in 1968 to 1969, only a few flares, creating insignificant to moderate increases in the galactic radiation level at SST altitudes, have been observed.

Because large solar flares occur infrequently and the peak of the radiation surge at SST altitude does not last longer than 1 hour at the most, the larger part of the total dose would accrue from galactic radiation—even when exposure at SST altitude is continuous during the period of maximum solar activity. Although complete protection from flare radiation by the avoidance of exposure requires a number of elaborate provisions, such provisions are entirely feasible and would merely entail very infrequent curtailments of SST service. On the other hand, the increased level of galactic radiation at conventional flight altitudes, and all the more at SST altitudes, is an ever-present phenomenon from which no means of protection exists. (The resulting exposure has to be accepted as the price of progress, as is the population's exposure to radiation from medical x-rays or from the use of atomic power.) Thus, the public health aspects of exposure to radiation at high altitudes center on galactic radiation.

Galactic Radiation

At sea level, galactic radiation contributes only about 4 microrads per hour to the ionizing radiation that occurs in nature. A much larger share, about 10 to 15 microrads per hour, depending on geological terrain, is due to gamma radiation from radioactive trace minerals in the ground. In an aircraft climbing to altitude after takeoff, the level of environmental gamma radiation rapidly decreases, with a half-value layer of about 400 feet in air of normal density at sea level. Since galactic radiation increases very slowly at first, the result is that the level of total environmental radiation actually decreases during the first part of the ascent from sea level to an altitude of about 3000 feet (Fig. 1). After the minimum amount of radiation is passed, galactic radiation becomes the sole source of environmental radiation.

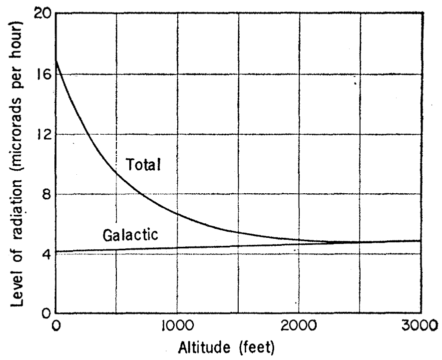

Fig. 1. The level of total environmental radiation and the galactic component, over sea-level terrain.

The shift from gamma radiation, which originates in the earth's crust to galactic radiation entails a complete change in the kinds of ionizing agents. Most important radiobiologically is the fact that sizable amounts of galactic radiation are produced by neutrons and low-energy protons and alpha particles released in nuclear collisions of primary galactic particles of high energy in tissue. Since the secondary particles, because of their high rate of ionization in tissue, are up to ten times more effective in producing tissue damage than primary particles with a low rate of ionization, the flux densities of the various types of secondaries of the galactic beam in the atmosphere do not reflect correctly their relative contributions to the total dose equivalent. It is for this reason that a large part of the data that physicists have been busy collecting for more than 50 years on the transition of galactic radiation in the atmosphere does not lend itself easily to a dosimetric evaluation. While the distribution of energy in the spectrum of galactic neutrons in the lower altitudes is fairly well established, reliable data on absolute fluxes are sorely needed.

Early estimates (*1*) put the dose equivalent of galactic neutrons at sea level at 0.6 microrem per hour. Watt (*2*) has reported measurements yielding the substantially higher value of 1.5 microrems per hour. For altitudes in the region of about 20,000 to 100,000 feet, flux densities of neutrons are better defined, although the data are still incomplete, especially with regard to the dependence of flux densities on latitude. The information clearly indicates that about half of the total galactic dose equivalent is produced by secondary neutrons. Still less well defined is the dose equivalent from disintegration stars in tissue. Here again, data of moderate accuracy, in terms of absorbed doses, turn into semiquantitative guesses when expressed as dose equivalents. The basic difficulty in appraising the aeromedical and public health implications rests in the fact that the extremely complex composition and the small flux densities of each of the many components of the degraded galactic beam within the atmosphere prohibit a straightforward measurement of the total dose equivalent with standard instrumentation. Instead, the total dose equivalent can only be established indirectly and from basically different kinds of experimental data—those on ionizing components in general and the so-called total ionization in particular, and those on flux densities of neutrons. A comprehensive review of the two kinds of data is far beyond the scope of this article. The reader is referred to the study of Neher (*3*), which summarizes the state of knowledge on the total ionization, and to the study of Holt, Mendell, and Korff (*4*), which presents the case of the dependence on latitude and altitude of the flux of cosmic-ray neutrons.

Even the indirect method of piecing together the total galactic dose equivalent from data on the total ionization and the neutron flux runs into a snag. While the conversion of flux densities of neutrons to dose equivalents poses no problem, the establishment of the dose from ionizing components remains equivocal, because it is quite difficult to identify what fraction of the total ionization is produced by neutrons. The most comprehensive data on the total ionization are those of Neher (*3*). They were gathered with a stainless steel ionization chamber that was filled with argon under high pressure. It is obvious that this chamber must substantially underrate the neutron contribution to the total ionization. Since neutrons, in terms of absorbed energy, contribute less than 10 percent of the total dose of galactic radiation, their heavily underrated, yet unknown, contribution to the total ionization in Neher's measurements could be left uncorrected for and the dose from neutrons, as it follows from the measurements of Korff's team, added in full, without committing a major error.

Another problem concerns the contribution that disintegration stars in tissue make to the total galactic radiation. In terms of absorbed energy, the contribution of stars is contained in the total ionization with only an approximate value, because a stainless steel argon chamber is not a tissue-equivalent system. The corresponding error appears in the dose equivalent, again magnified by a quality factor of 10. Thus, the process of adding up the total galactic dose equivalent from a number of very different components involves estimates in at least two instances. Rather than conduct a lengthy evaluation of upper and lower limits of the estimates in question, I feel that an intuitive compromise will serve the purpose of appraising the public health implications sufficiently well and more expeditiously. Figure 2 presents an attempt at such a compromise.

Although Fig. 2 is self-explanatory, it does not convey information on the changes in the galactic radiation field with the solar cycle. The graph shows conditions only for the solar minimum; that is, for the phase of the solar cycle in which the galactic flux is at its maximum. At solar minimum, the interplanetary magnetic field created by the solar wind is weak. Therefore, galactic particles of lower energies, which are prevented from reaching the inner planets by the stronger field at solar maximum, are admitted. Since this "screening" affects mainly particles of lower energies (that is, of lower powers of penetration) the influence of the solar cycle is very pronounced at high altitudes, yet almost completely absent at sea level. The flat maximum of 1650 microrems per hour at altitudes of 80,000 to 100,000 feet and at high latitudes (Fig. 2) is based on measurements reported by Foelsche *et al.* (*5*). The same authors report for solar maximum a dose equivalent rate of 1200 microrems per hour in this region. The ratio of 1.375 (based on the two values) for the influence of the solar cycle appears low in comparison to the value of 2.0, which follows from other data. This is another parameter of the galactic radiation field in the atmosphere which badly needs additional measurements.

With the galactic radiation field throughout the earth's atmosphere mapped completely, it is merely a computational task to establish the pertinent integral dose equivalents for typical flight routes and time-altitude profiles. The great circle routes between San Francisco and Stockholm and between Sydney and Acapulco are the preferred examples of representative flight patterns through the regions of highest and lowest levels of galactic radiation.

A general appraisal of accumulated exposures per year under a typical set of conditions would seem to be more interesting than a collection of sample exposures; however, before I proceed to that appraisal, an interesting argument should be discussed. Jet propulsion with air-breathing engines requires higher air speeds for higher cruising altitudes if the same mass of air for combustion is to be scooped up per unit of time. Plotting cruising altitudes and air speeds for two conventional passenger jets and two SST's in Fig. 3, one obtains a rectilinear relation. Plotting the level of galactic radiation over the same altitude scale, one obtains a curvilinear relation, with the radiation level increasing more slowly at higher altitudes. This leads to the intriguing result that the level of galactic radiation per mile for the SST is smaller than that for the conventional jet. The SST encounters a higher level of radiation, but it travels so much faster that the integral dose accumulated over the same distance is smaller. To be sure, the argument must be taken with a grain of salt. As faster airplanes are put into service, a crew member or a businessman or a person fond of air travel is more likely to spend approximately the same total amount of time per year in air travel than to travel the same total distance per year. It is common

Table 1. Population doses from radiation occurring in nature and man-made additions.

Source of radiation	Dose equivalent (millirems per year)
Natural	110
Medical x-rays	55
Fallout	10
Radiation workers	0.56
SST travel*	0.36

* Assuming 77 million passenger hours at altitude.

practice in commercial air traffic to report the volume of traffic in revenue passenger miles per quarter rather than in passenger hours. If population doses are to be assessed and projected into the future, the number of passenger hours at altitude is the relevant quantity.

Public Health Aspects

For an overall estimate of the exposure of SST crew members to galactic radiation, one might assume 480 hours per year at altitude and an average radiation level of 100 microrems per hour as conservatively high, representative values. The resulting yearly does of 0.480 rem falls slightly short of the official maximum permissible dose (MPD), as determined by the International Commission on Radiological Protection, of 0.5 rem for the public (*6*). Since a safety margin of 4 percent below the full allowance would appear quite narrow, it might be advisable to consider SST crew members as "radiation workers," in the terminology of the Commission. This would make an MPD of 5 rems per year applicable to SST crews and establish a safety margin that could cover even a large solar flare.

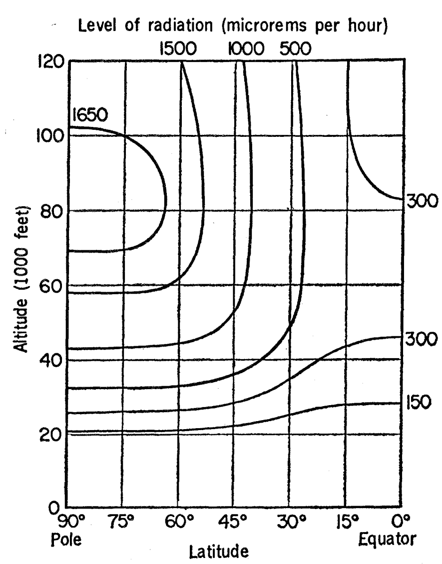

Fig. 2. The galactic radiation field in the earth's atmosphere, from sea level to 120,000 feet.

Conditions in regard to the population dose are more complex. Since there are always substantially larger numbers of passengers than crew members in the air, the bulk of the population dose is contributed by passengers. Official records indicate that in 1969 the commercial aircraft of the United States flew a total of 131.4 billion revenue passenger miles. This entire volume of traffic, if projected to SST altitude at the speed of the Concorde, would correspond to 77.2 million passenger hours at altitude, or 77,200 man rems. Dividing this by 210 million—the population of the United States—one arrives at a population dose of 0.36 millirem per capita per year.

Besides exposure at high altitudes, three other man-made additions to the ionizing radiation that occurs in nature are affecting the population. In order of importance, they are medical x-rays, fallout, and exposure of radiation workers. Table 1 shows a lineup of these three man-made additions, along with exposure at high altitudes and the ionizing radiation that occurs in nature. Exposure at high altitudes does not constitute a significant quantity in the grand total of exposure from man-made sources. On the other hand, it is interesting to note that exposure at high altitudes ranks closely behind the exposure of radiation workers. Since the latter exposure is very thoroughly monitored, it would also seem advisable to keep accurate records on the exposures at high altitudes. To be sure, the two additions, although similar in magnitude, show very disparate distributions, since they accrue from population groups of vastly different sizes. They also differ basically with regard to the potential hazards of serious excesses of the MPD. In nuclear installations, accidents that can lead to very large, instantaneous exposures of personnel constitute a definite, ever-present threat. Quite differently, large transgressions of the MPD in acute exposures can never occur as far as galactic radiation is concerned. Transgressions will be extremely infrequent and of a comparatively more moderate magnitude, even as far as solar flares are concerned.

The 480 hours per year at altitude assumed for SST crew members represent 5.5 percent of the total time of a year. It seems safe to assume that few, if any, passengers would match or exceed that percentage. Yet even in the extreme case of someone's spending, for a full year, 10 percent of his time at SST altitude, the integral dose equivalent would still not exceed 1 rem. These inherent safeguards in the exposure at high altitudes, excluding completely the possibility of injury from acute radiation, certainly would seem to justify dispensing with all direct monitoring of exposure to galactic radiation, even in the SST. Establishing the resulting population dose by computation from statistical data, flight logs, and a tabulation of the galactic radiation field in the atmosphere would appear to be entirely satisfactory from the standpoint of public health.

A final task remains. Although by now we expect it to be insignificant, the radiobiological risk factor involved in the exposure to galactic radiation at SST altitude has to be spelled out. Because we are dealing with a typical long-term exposure at very low dose rates, only subtle, late effects, such as a slight increase in the incidence of leukemia (or malignancies in general) or a token abbreviation of the life-span, could develop. Formulated specifically for SST crew members, the risk factor of an occupational exposure of about 0.5 rem per year has to be assessed. Applying linear regression to data from survivors of Hiroshima and Nagasaki and from patients undergoing radiation therapy, radiobiologists estimate the leukemogenic efficiency of ionizing radiation at one to two cases per million per rem per year (*7*). Thus, if 1 million people receive a dose of 1 rem each, there will occur among them, in the year following the exposure, one to two cases of leukemia that would not have occurred without the exposure. Compared to the normal incidence of leukemia in the United States [70 to 120

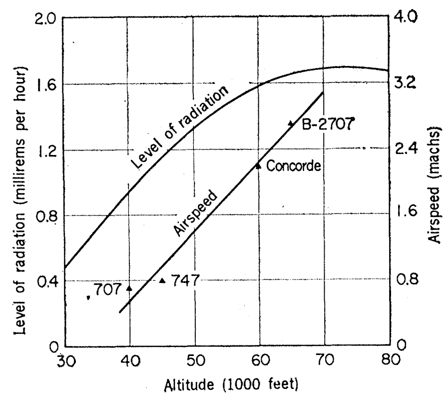

Fig. 3. The level of galactic radiation and the cruising speeds of conventional jet and supersonic transport, as functions of altitude.

cases per million per year (*8*)], the exposure in question is seen to produce an increase in risk of 1 percent. That is a very small increase indeed. It must be pointed out again that this figure is based on linear regression; that is, on the assumption that there is no safe dose for leukemia below which the effect is zero.

Equally insignificant is the increase in risk in terms of shortening the residual life-span. Again, direct experimental information for very low doses is not available, and one must resort to linear extrapolation from protracted exposures to medium and high dose levels. Additional uncertainty results from the fact that elaborate data are available only for the mouse. Therefore, the additional hypothesis has to be made that the two species, man and mouse, have the same sensitivity to a radiation-induced shortening of the life-span. With these restrictions, current estimates for man of a shortened life-span caused by exposure to radiation range from 10 days per rem for acute exposure to 2.5 days per rem for chronic exposure (*7*). Since a substantial fraction of the galactic radiation at altitude is produced by neutrons and low-energy protons and alpha particles (that is, by particles with a high rate of ionization for which the lower efficiency of chronic exposures at low levels of galactic radiation is questionable), it seems safer to apply the higher value of 10 days per rem to the yearly dose of 0.5 rem from galactic radiation. In doing so, one arrives at a figure of 5 days for 1 year, or a shortening of the life-span by 1.4 percent per year. Again, this is a marginal enhancement of risk and remains well within the limits considered acceptable in the official definitions of MPD's.

A more detailed discussion of the philosophy of risk versus gain in setting "safe" limits for harmful environmental influences will not be undertaken here. In this case, it would merely be an exercise in dialectic, in view of the fact that the radiation in question ranks lowest among all man-made additions to the amount of ionizing radiation that occurs in nature. It should be pointed out, though, that the problem is one of modern aviation in general. It would be quite artificial to consider the step from the conventional jet to the SST as a basic change in terms of the levels of environmental radiation and to build on it an argument against the SST.

References

1. *Protection Against Neutron Radiation up to 30 Million Electron Volts* (National Bureau of Standards Handbook No. 63, Government Printing Office, Washington, D.C., 1957), p. 13.
2. D. E. Watt, *Health Phys.* **13**, 501 (1967).
3. H. V. Neher, *J. Geophys. Res.* **72**, 1527 (1967).
4. S. S. Holt, R. B. Mendell, S. A. Korff, *ibid.* **71**, 5109 (1966).
5. T. Foelsche, R. Mendell, R. R. Adams, J. W. Wilson, *RIF:FAUSST 7.3.3.02* (NASA Langley Research Center, Hampton, Virginia, 1969).
6. *Radiation Protection: Recommendations of the International Commission on Radiological Protection* (ICRP Publication No. 9, Pergamon, New York, 1966).
7. *Radiobiological Factors in Manned Space Flight*, W. H. Langham, Ed. (Publication No. 1487, National Academy of Sciences, Washington, D.C., 1967).
8. E. B. Lewis, *Science* **125**, 965 (1957).