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Radiation Safety Aspects of Commercial High-Speed Flight Transportation

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Acronyms and Symbols

BEIR	U.S. National Academy of Science Committee on the Biological Effects of Ionizing Radiations
DREF	dose rate effectiveness factor
FRA–NRT	Frankfurt to Tokyo (Narita)
HSCT	high-speed civil transport
ICRP	International Commission on Radiological Protection
LaRC	Langley Research Center
LET	linear energy transfer
LHR–ANC	London Heathrow to Anchorage
LHR–NYC	London Heathrow to New York City
NCRP	National Commission on Radiation Protection
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
RBE	relative biological effectiveness
UNSCEAR	United Nations Scientific Committee on Effects of Atomic Radiation
a	cell radius
D	dose to tissue
$\dot{D}$	dose rate
D_d	dose for which 37 percent of cells survive
D_{eq}	equivalent gamma ray dose
D_t	transformation sensitivity
H	dose equivalent
$\dot{H}$	dose equivalent rate
H_E	equivalent dose
L	linear energy transfer (LET)
$P_d(t)$	probability of cell killing
$P_T(t)$	probability of transformed cell being formed
Q	quality factor
$\overline{Q}_i$	average quality factor
$(\mathrm{RBE})_M$	maximum relative biological effectivenss
t	transverse distance or radius
W_R	radiation weighting factor
Z	ion atomic number

Abstract

High-speed commercial flight transportation is being studied for intercontinental operations in the 21st century. The projected operational characteristics for these aircraft are examined, the radiation environment as it is now known is presented, and the relevant health issues are discussed. Based on a critical examination of the data, a number of specific issues need to be addressed to ensure an adequate knowledge of the ionizing radiation health risks of these aircraft operations. Large uncertainties in our knowledge of the physical fields for high-energy neutrons and multiply-charged ion components need to be reduced. Improved methods for estimating risks in prenatal exposure need to be developed. A firm basis for solar flare monitoring and forecasting needs to be developed with means of exposure abatement.

Introduction

High-speed flight research in support of the development of an economically competitive and environmentally sound supersonic transport is a high priority within NASA aeronautical programs (ref. 1). The commercial target for this aircraft is the rapidly growing international travel market which would support 500 to 1000 aircraft worth $200 billion in manufacturing orders. Environmental issues including sonic boom, terminal noise, and impact on the ozone layer are being addressed (refs. 2 and 3). The problem of ionizing radiation exposure at subsonic flight altitudes has received recent worldwide attention (ref. 4) because of the recommended lowering of exposure limits (refs. 5 and 6) and focuses the need to examine more closely the impact of the significantly higher ionizing-radiation levels and the peculiar nature of the radiations present at the much higher supersonic flight altitudes (60 000 to 80 000 ft). The present report examines our current state of knowledge of the high-altitude environment and its impact on supersonic flight operations.

When the possibility of high-altitude supersonic commercial aviation was first seriously proposed, Foelsche (ref. 7) brought to light a number of concerns with respect to atmospheric ionizing radiation. Subsequently, a detailed study of the atmospheric ionizing-radiation components at high altitudes was conducted from 1965 to 1971 at the Langley Research Center (LaRC) by Foelsche et al. (ref. 8). Prior to that study the role of atmospheric neutrons in radiation exposure was generally regarded as negligible (ref. 9). However, the neutrons were found in the LaRC study to be the major contributor to aircraft exposures. This study utilized an instrument package consisting of tissue equivalent ion chambers, organic scintillator neutron spectrometers, and nuclear emulsion. A theoretical program to predict atmospheric radiation levels and to specifically extend the neutron spectrum into the range outside that measured by the scintillator spectrometer was also developed (ref. 10). The fast neutron spectrum (1 to 10 MeV) due to galactic cosmic rays was found to be nearly independent of solar modulation. However, the neutron spectrum produced by solar cosmic rays was found to vary from event to event. An overview of that program is given by Foelsche in reference 11. The conclusion of this previous work was that high-altitude commercial aviation required special considerations for radiation protection (refs. 12 through 14), whereas the most exposed flights for pre-1980 subsonic airlines were well within the exposure limits of the general population (refs. 8, 12, and 14).

Several factors have changed since those studies: (1) the highly ionizing components are found to be more biologically damaging than previously assumed and the associated quality factors have been increased (refs. 6 and 15); (2) recent epidemiological studies (especially data on solid tumors) and more recent atomic bomb (A-bomb) survivor dosimetry have resulted in higher radiation risk coefficients for gamma rays (refs. 16 and 17) so that reduced permissible exposure limits are being proposed (refs. 5 and 6); (3) "an urgent need is recognized for better estimates of the risk of cancer from low levels of radiation" (ref. 18); (4) subsequent to deregulation of the airline industry, flight crews are logging greatly increased flight hours (refs. 19 through 24); (5) a new class of long-haul commercial aircraft is being developed on which personnel for two crew shifts will be simultaneously aboard a single flight leading to increased exposures for a fixed number of flight duty hours (ref. 25); and (6) airline crew members are now classified as radiation workers (refs. 6

and 26). Although the Langley database on biologically important radiation components appears to be the most complete and comprehensive available, at present, updating with new quality factors, addition of previously unresolved radiation components, and providing for easy use by the health physics community are required (ref. 27). Since the commission of these past measurements about 30 years ago, no systematic studies of the physical fields present in the stratosphere have been made. As a result of renewed interest within NASA in high-altitude aircraft such as the National Aero-Space Plane, the High-Speed Civil Transport (HSCT), and the Hypersonic Transport (refs. 28 through 30), a review of the present state of knowledge seems appropriate. The purpose of the present report is to review our current knowledge of the radiation environment in the upper atmosphere and its impact on radiation safety of passengers and crew. Necessary research to fill gaps in our understanding is identified to support a High-Speed Civil Transport radiation safety assurance program.

Establishing a policy for the radiation safety of high-speed aircraft is beyond the purview of this report. In view of the evidence presented herein and the prevailing issues surrounding even subsonic aircraft as a result of the lowering of accepted exposure limits in the face of rising quality factors, it seems clear to the authors that a policy should be defined to address the issues involved. These issues are the ones we attempt to bring to light, and several questions that may help in establishing the required policy are now posed:

1. How will the acceptance of newly proposed exposure limits and quality factors (or weighting factors) affect the potential use of the high-speed aircraft in the international commercial market?
2. How will sufficient information be presented to individual pilots to ensure passenger safety in the event of a large solar particle event?
3. To what degree should NASA consider the uncertainty in radiobiological response to this unique radiation environment associated with these aircraft?
4. To what degree should NASA consider the environmental uncertainty associated with these aircraft?
5. How will exposure data for flights and individual crew members be generated for career planning and possible litigation?

We will not attempt to formulate answers to these questions or to formulate a policy, but rather we will examine our present state of knowledge in an effort to clarify the technical issues involved.

Basic Concepts in Radiation Protection

This report will be read by those both familiar and unfamiliar with ionizing-radiation protection. Therefore, to make the report more useful to the nonspecialist, this section is a simplified, brief outline of a far more complex issue and may be disregarded by the specialist. Furthermore, we limit our discussion to only those topics which are applicable to high-altitude aircraft exposure.

Human Response to Radiation

The human response to ionizing radiation on which protection standards are currently based is mainly fatal cancer risks and, to a lesser degree, developmental injury. Cancer induction is referred to as a "stochastic effect" because the tumor progresses from a single cell transformed by the radiation field. The cell transformation is a rare statistical event, the probability of which increases with increasing exposure.[1] The severity of stochastic injury is independent of the exposure level. In distinction, developmental injury is referred to as a "deterministic effect" which results from damage to whole tissues during organogenesis. It can result from the killing of progenitor cells or from altered gene expression in which cell differentiation and structural formation are affected. Unlike stochastic effects, the level of severity of deterministic injury increases with increasing exposure. Other biological end points, such as embryonic lethality, may yet have impact on future regulatory standards as information on biological injury improves (ref. 31).

The primary source of knowledge on human radiation risk is from the exposure data of the two nuclear weapons of World War II. The primary data on fatal cancer risk and mental retardation in prenatal exposure are from analysis of the A-bomb radiation exposures (refs. 16 and 17). Because of the latency of progression from single transformed cell to clinical tumor and improvement in estimates of the exposure fields in the A-bomb detonations, there has been a steady increase in estimates in radiation-induced risk coefficients for excess fatal cancer (number of excess fatal cancers per 100 exposed individuals per Gy of gamma ray exposure) as shown (ref. 32) in figure 1.

[1] Exposure is a field quantity related dose (later, dose equivalent) in a small tissue mass. (See ref. 8.)

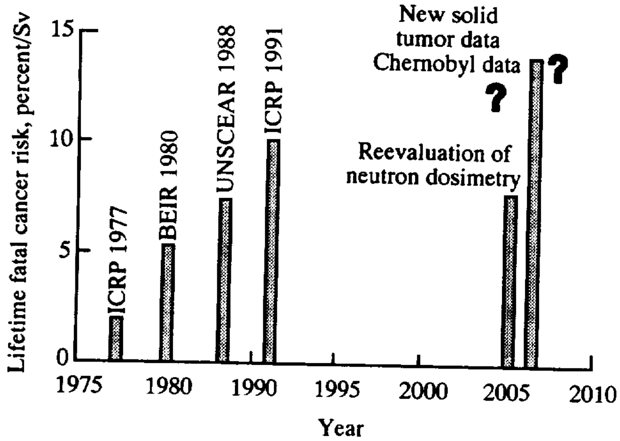


Figure 1. Trends in estimated fatal cancer risk coefficient.

More recently, data compiled on nonfatal cancer will undoubtedly have future effects on protection standards (ref. 33). The projection of such trends into the future is difficult. For example, the latest A-bomb dosimetry reduced the neutron dose estimates; this caused an increase in the estimated risk coefficient (ref. 17). The risk may decrease as knowledge of the A-bomb exposure levels improves. For example, there is evidence that neutron exposures in the Hiroshima event may be larger than estimated in the 1986 evaluation (ref. 34), which, if validated, would lead to smaller risk coefficients. In contrast, risk coefficients may continue to increase as the epidemiological data become more complete or as data from the Chernobyl exposures are collected. Data on childhood leukemia from prenatal exposure are mainly from diagnostic X-ray data (ref. 35) and are consistent with the A-bomb exposure data (ref. 17). None of these human exposure data contain significant contributions from neutrons or multiply-charged ions, the effects of which must be estimated from additional sources, such as animal experiments.

Exposure Limits

Exposure limits are defined so that radiation-induced fatal cancer risks are limited to on the order of or less than the fatal accident risks of ordinary occupations (on the order of 10^{-4}/yr, ref. 36). Correspondingly, the increase in the fatal cancer risk coefficient (fig. 1) causes a corresponding decrease in allowed exposure limits, but the relation is modified by a dose rate effectiveness factor (DREF, the factor by which the biological effect is reduced as a result of prolonging the exposure period at a greatly reduced dose rate). This factor arises because the human response database is for acute exposures in distinction to career exposures obtained in small fractions over many years to which exposure limits are applied. Risks are generally greater for acute exposures as opposed to exposures over several years. The dose rate effectiveness factor for human gamma ray exposure used by various groups is a conservative value ranging from 2 (ref. 17) to 2.5 (ref. 36) and is observed in animal experiments to vary from 2 to 10 (ref. 17). The DREF is an added source of uncertainty in relating the acute exposure response data to chronic career exposure limits.

Since the current standards for the nuclear industry were established in the United States as shown in table 1 (ref. 37), new epidemiological studies especially of the A-bomb survivors and a reevaluation of the A-bomb dosimetry have been made. The result of

Table 1. Current and Projected Maximum Allowable Exposure Limits

	Maximum allowable exposure, mSv			
Exposure condition	Present United States 10 CFR Part 20 (ref. 37)	Proposed United States NUREG/BR-0117 (ref. 38)	Proposed NCRP rep. 116 (ref. 4)	Proposed ICRP publ. 60 (ref. 6)
Occupational:				
Annual	[a]50	50	50	20
Lifetime	[50 (Age − 18)]		[b]10 × Age	
Pregnancy (total)	5	5		[c]2
Pregnancy (monthly)			0.5	
Public:				
Annual, many years	[d]1	1	1	1
Annual, occasional		5	5	
Pregnancy (total)		5		[c]2
Pregnancy (monthly)			0.5	

[a]Not to exceed 30 mSv in any quarter year.
[b]Recommended limit for new designs is 10 mSv/yr.
[c]Abdomen surface for X-rays, 1 mSv *in utero*.
[d]5 mSv allowed with prior approval of NRC.

the latest dosimetry reduces the contributions from neutron exposures in the A-bomb data to be near negligible. Thus, the A-bomb exposures are now estimated to be mainly from gamma rays. The latest resulting health risk coefficients are given by the UNSCEAR report (ref. 16), BEIR V report (ref. 17), and the ICRP (ref. 6). New standards have been proposed for the U.S. (refs. 5, 38, and 39) and internationally (ref. 6) as shown in table 1. Only the last column of limits proposed by the ICRP are specifically recommended for aircraft operations (ref. 6).

Strictly speaking, the exposure limits in table 1 are based on risks due to gamma ray exposures at high dose rate and a conservative DREF. The problem of extrapolation to other radiation types is discussed in the next section.

Quality Factors and Weighting Factors

Gamma ray exposures occur through small quantal releases of energy randomly dispersed within the cell. The greater fraction of the cell volume is relatively insensitive to radiation injury, and reasonably high exposures to gamma rays (many gamma ray traversals) are required to result in injury of the small sensitive sites within the cell. Since many gamma ray traversals are implied, the rate of traversal is an important factor in the resulting injury because the cell can efficiently repair damage in small quantities. In distinction, the more heavily ionizing particulate radiation deposits relatively large quantities of energy per unit pathlength (linear energy transfer (LET)) and is able to damage a sensitive site with a single traversal. Consequently, the rate of arrival of high-LET particles is less important as a determinant in resultant injury. The absorbed dose always relates to the energy deposits per traversal multiplied by the number of traversing rays. The dose from gamma rays (the energy deposit is dispersed evenly over the cell) relates to the accumulation of sufficient energy within a sensitive site to result in biological injury, whereas dose for heavily ionizing particulate radiation relates to the probability that the sensitive site was in fact hit by the traversal. For heavily ionizing particles, the energy deposit lies close to the particle path. A given level of injury can be achieved by different dose levels of different radiation types and different dose rates. The relative biological effectiveness (RBE) is defined as the ratio of dose of gamma rays to the dose of radiation type i (for a given dose rate) which results in the same injury level and the RBE is strongly correlated to the LET and exhibits strong dose rate dependence as expected from the previous discussion. Since gamma rays are less efficient in causing injury at low dose rate, the RBE will increase for decreasing dose rate and presumably reach a maximum ($(\mathrm{RBE})_M$). The RBE is used to extrapolate the human exposure risk coefficients for gamma rays to arbitrary radiation types.

The RBE depends on the biological end point being tested in addition to the radiation type. The RBE for the specific environmental components is related to radiation risks but cannot be evaluated in controlled human experiments. Estimates of RBE for specific biological end points are evaluated with animal and cell models and always provide some uncertainty in application to estimation of risks in human exposures. Values of the estimated maximum $(\mathrm{RBE})_M$ are given in table 2 for various biological end points for fission neutron exposures (ref. 15). One should keep in mind that $(\mathrm{RBE})_M$ relates not only to the effectiveness by which high-LET radiation can cause injury but to the ability of the biological system to repair injury from low dose rate gamma ray exposure (that is, $(\mathrm{RBE})_M$ is proportional to DREF).

Table 2. $(\mathrm{RBE})_M$ for Fission Neutrons

Tumor induction	≈3–≈200
Life shortening	15–45
Transformation	35–70
Cytogenic studies	40–50
Genetic end points in mammalian systems	10–45
Other end points:	
Ocular lens opacification	25–200
Micronucleus assay	6–60
Testes weight loss	5–20

The RBE is the result of an experimental measurement and is most closely related to risk. The quality factor (or the more recently introduced weighting factor) is a defined quantity by the judgment of an august committee for use in radiation protection. The quality factor is a unique function of LET (fig. 2) and applicable to stochastic end points (e.g., fatal cancer). A quality factor for developmental injury has not been defined and the need for such a factor is discussed further.

The precisely defined relationship of quality factor to LET has, according to the ICRP (ref. 6), lead to assumptions that the quality factor is known to greater precision than is warranted by the available data on RBE. Consequently, the ICRP recommends against the use of quality factors and recommends an alternative approach through the use of the radiation weighting factors W_R in table 3 for radiation protection practice. Furthermore, note that the use of the

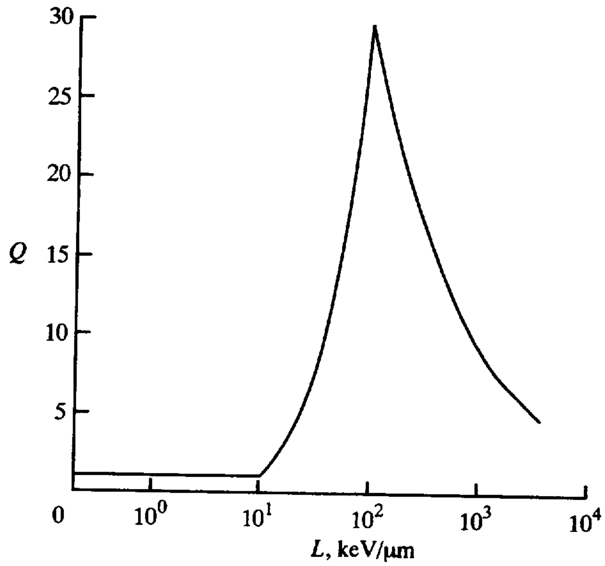


Figure 2. Currently recommended quality factor (ref. 6).

quality factor to estimate fatal cancer risks should include the caution that such risk estimates contain large inherent uncertainties.

In summary, radiation risks are related to the equivalent gamma ray dose D_{eq} given in terms of the RBE values for each radiation component of dose D_i as

$$D_{eq} = \sum_i (\mathrm{RBE})_i D_i \tag{1}$$

where the gamma ray risk coefficients are taken from epidemiological studies. Older recommendations for radiation protection would limit the exposures estimated by the dose equivalent H as

$$H = \sum_i \int Q(L) \frac{dD_i}{dL} \, dL \tag{2}$$

where $Q(L)$ is the corresponding quality factor for LET value L as shown in figure 2 and the sum over each radiation type i. The latest ICRP-recommended exposure estimates use "equivalent dose" H_E in terms of weighting factors

$$H_E = \sum_R W_R D_R \tag{3}$$

where R denotes the radiation components noted in table 3. Note that risk estimates require knowledge of the physical properties of the radiation fields and their associated RBE values and use of equation (1). Use of equation (2) or (3) implies dosimetric methods and incorporates large inherent uncertainty in risk estimates by virtue of introducing the quality or weighting factor.

The defined quality factors and weighting factors are given for only stochastic end points (cancer risks). Because of the possibility of exposure during pregnancy, many of the concerns are for deterministic (developmental) effects for which quality and weighting factors are currently undefined. Recent experiments with mice embryo hemopoiesis reveal large RBE for alpha particles that cause severe development injury (ref. 40). Such effects would be underestimated by a factor of 10 to 20 if the stochastic quality factors are used (ref. 40). As we will show, the high-altitude exposures are dominated by highly ionizing (large LET) particulate radiation and appropriate quality factors for developmental injury are a critical issue.

Radiation Environment

The normal radiations (background) present in the upper atmosphere are produced by galactic cosmic rays incident from above. During periods of increased solar activity, some solar flares produce large fluences of ions of modest to high energies which, if they intersect the Earth, can cause large localized

Table 3. Recently Recommended Radiation Weighting Factors

Radiation component	W_R from—	
	ICRP publ. 60 (ref. 6)	NCRP rep. 116 (ref. 5)
X- and γ-rays, electrons, positrons, and muons	1	1
Neutrons with energy of—		
<10 keV	5	5
10 to 100 keV	10	10
>100 to 2 MeV	20	20
>2 to 20 MeV	10	10
>20 MeV	5	5
Protons with energy of—		
>2 MeV	5	2
Alpha particles, fission fragments, and nonrelativistic heavy nuclei	20	20

transients in atmospheric radiation levels. The remote possibility is always present that a high-altitude nuclear test will result in contamination of exterior surfaces of the airplane and the cabin interior if air filtering is inadequate.

Background Radiation Levels

The background radiation levels are generated in the high atmosphere by the galactic cosmic rays consisting of energetic nuclei (ions) of all of the known elements (ref. 41). The dominant ions are protons (≈90 percent) with significant numbers of alpha particles (≈10 percent). The remaining ions (few percent) consist of all the elements having atomic numbers through uranium. The energy spectrum of the cosmic radiations is very broad and their energies exceed 10^{18} eV. Two thirds of the ionic energy transported into the atmosphere is carried by the proton flux. The remaining one third is almost equally divided among the alpha particles and heavier ions.

The galactic cosmic rays have two barriers to overcome before arrival at the atmosphere of the Earth. The first barrier is the interplanetary plasma with its magnetic irregularities produced by the expansion into space of the solar plasma in which the local solar magnetic field is frozen. The properties of the interplanetary plasma are determined by the plasma emission at the solar surface and vary over the solar sunspot cycle shown in figure 3. The second barrier is the geomagnetic field. Near the geomagnetic equator, incoming ions tend to be deflected back into space before reaching the atmosphere. Only the most energetic ions and the ions with the least ratio of charge to mass (complex nuclei) are able to penetrate the geomagnetic field in equatorial regions. Near the geomagnetic poles, the geomagnetic field lines are vertical and ions of all charges and energies follow helical trajectories into the atmosphere where the most intense atmospheric radiation levels are found in the polar regions. During times of solar geomagnetic storms, the easy access to the atmosphere at the poles is extended to middle latitudes; this causes large increases in dose rates at those latitudes.

The dose equivalent is defined (eq. (2)) as the sum of the dose from each radiation component D_i times the corresponding average quality factor $\overline{Q}_i$, which is a weighting factor (ref. 6) that indicates some radiations produce a higher biological risk for a given absorbed energy. Our current knowledge on biological response consists of a combination of experimental data and theoretical models. The method by which these are combined for an estimate of stratospheric exposure is now defined. The dose to tissue (energy absorbed per unit mass) is approximated by measuring the electrical current in a tissue equivalent ion chamber and consists of many contributions as

$$D = D_\gamma + D_e + D_\mu + D_\pi + D_n + D_p + D_d + D_t + D_{\text{He}} + D_{\text{Li}} + \ldots \tag{4}$$

where the successive terms refer to dose from gamma rays, electrons, muons, pions, neutrons, protons, deuterons, tritons, helium ions, lithium ions, and other multiply-charged ions. The dose is not a good indicator of biological injury because many of the contributing particle types have RBE values which are greater than unity. We estimate the biological effectiveness herein by use of the quality factor given in equation (2). We use computational models to estimate many of the individual components in equation (4) and the average quality factor for each type by equation (2). The dose equivalent is obtained by adding individual dose contributions with their associated quality factors and may be arranged in the following format:

$$H = D + \sum_i (\overline{Q}_i - 1) D_i \tag{5}$$

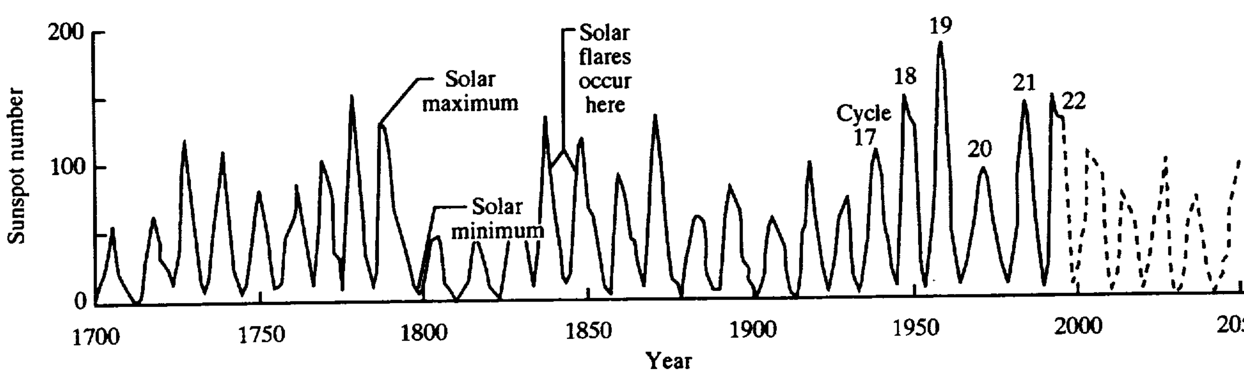


Figure 3. Variation of sunspot number over last few centuries. Dashed curve denotes extrapolation.

where the sum now contains contributions only from particles whose quality factors are greater than unity. Note, this is the same procedure used in reference 8. The basic data used in the current estimates are now described.

Air ionization. The air ionization was measured during the 1950's and 1960's in steel-walled, argon-filled ion chambers (the steel-argon combination was used to minimize wall effects and could be operated at high pressure). (See refs. 42 and 43.) The ion chamber responds well to the charged-particle environment but is virtually transparent to the biologically important neutrons. (Note, the main mechanism for transferring neutron kinetic energy into tissue dose is through collision with the hydrogen constituents of tissue, which are not present in the steel-walled ion chamber.) The accepted accuracy of the air ionization measurements is 5 to 10 percent. Measurements made during solar cycle 19, including detailed latitude surveys near solar minimum (1954) and solar maximum (1958), are used in the present estimates.

Atmospheric neutrons. The fast neutrons (1 to 10 MeV) were measured (refs. 8 and 44) with anticoincidence encapsulated scintillation counters and pulse shape discrimination for rejection of charged particle and gamma ray events. The estimated detector-response functions were known to 10 percent over their limited calibration range, and a few percent drift was observed during flights in balloons and various aircraft. The fast neutron flux was measured during the solar cycle 20 (fig. 3) from solar minimum (1964) to solar maximum (1968) and through the solar-activity decline to 1971. Extensive surveys as a function of latitude were made near solar minimum and maximum.

The neutron spectrum was extended below 1 and above 10 MeV by Monte Carlo transport-code calculations (ref. 8) as shown in figure 4. Only about 25 to 30 percent of the contribution to dose or dose equivalent was contributed by the measured fast spectrum. The remaining 70 percent of the neutron exposure rests on unverified theoretical predictions made by scaling proton reactions to approximate neutron production from multiply-charged ions. If one assumes that this scaling procedure is accurate then the biological exposure is accurately known from current environmental measurements (ref. 27). A recent analysis by Reitz (ref. 45) has emphasized the uncertainty in the neutron spectrum especially above 10 MeV. Recent experiments on neutron yields in heavy ion collisions show that this procedure is a poor approximation as shown in figure 5. Clearly the niobium cross section (ref. 46) is not proportional to the cross section for protons (ref. 47) since their spectral shapes are entirely different. The high-energy neutrons may be significantly underestimated by the scaling procedures used in deriving current atmospheric environmental models (refs. 10, 11, 22, and 27).

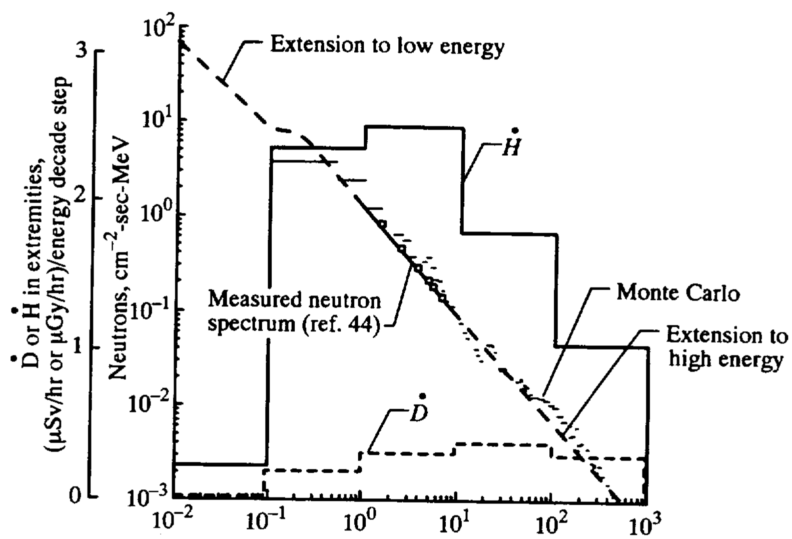


Figure 4. High-altitude (Geomagnetic latitude ≈ 69°) neutron spectrum, dose rates, and dose equivalent rate measured and calculated at HSCT altitudes (≈50 g/cm^2 or 70 000 ft) on August 3, 1965.

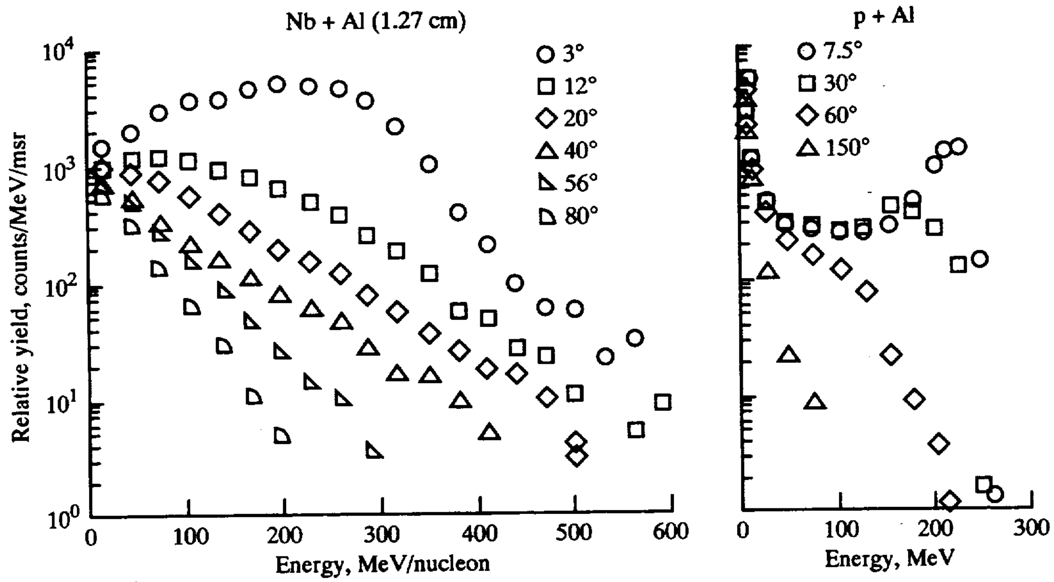


Figure 5. Neutron production spectra from 250 MeV/amu reactions in Al with Nb and proton beams.

The neutron spectrum was measured by Hewitt et al. (ref. 48) by using Bonner spheres and is shown in figure 6 with a compilation of results from several sources (ref. 45). Clearly the high-energy spectrum ($E > 10$ MeV) is uncertain by a factor of 5 (dashed lines), a fact of critical importance to neutron exposure estimates. A modern estimate of the calibration of the Bonner spheres and recently improved analysis techniques indicate that the inferred spectra of Hewitt et al. are too low in the 100 MeV region; this makes the already important high-energy neutrons possibly the dominant player in biological exposure. Clearly, the high-energy neutron spectrum uncertainty needs to be resolved (refs. 4 and 45).

Tissue ionization. The tissue equivalent ion chamber is a plastic-walled chamber with a methane and nitrogen fill to simulate tissue equivalence. Although the tissue equivalent ion chamber was used on relatively few flights, it provides a sufficient database to test the accuracy of the combined use of air ionization rate and neutron flux to estimate tissue ionization dose. Tissue ionization estimates from air ionization and fast neutron flux data agree to within 15 percent (refs. 8 and 27). It must be emphasized that this ion chamber measures tissue dose (energy absorbed per unit mass) and does not include the important biological modifying factors (RBE, quality factor). These factors are discussed more fully in a subsequent section.

Target fragmentation. Among the most damaging radiation constituents are the nuclear-reaction

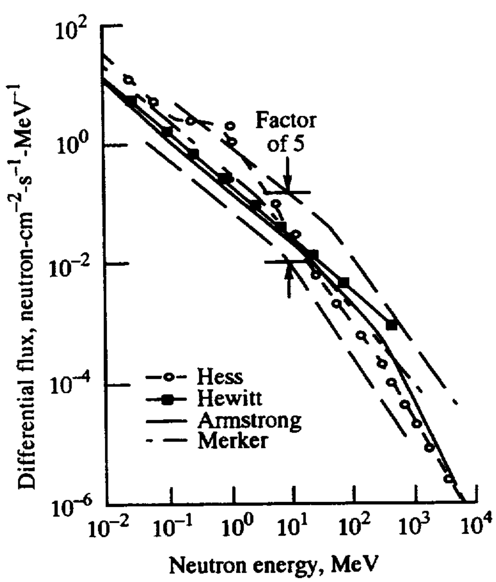


Figure 6. Neutron spectrum measured by Hewitt et al. with a spectrum measured by Hess and calculated by Armstrong et al. and Merker et al. (Data from ref. 45.)

products produced by reactions with biological tissue (refs. 49, 50, and 51). The fragment contributions in current atmospheric models were estimated by observing nuclear reactions in the gel molecules (amino acids and water) of nuclear emulsions. The theoretical ratios of nuclear fragmentation by protons to that of neutrons were used to estimate the charged-particle contribution. The average quality factor for the charged components due to nuclear stars (referred to as "stars" because of their appearance in nuclear emulsion) was then found from the emulsion data. These quality factors were used to extrapolate the air ionization data to nuclear star dose equivalent in time, latitude, and altitude. This method was used for the limited experimental data set and could be improved.

Multiply-charged ions. Although the iron group ions at the top of the atmosphere contribute nearly half of the biologically important radiation exposure, they will typically suffer two to three nuclear events before reaching stratospheric cruise altitudes of commercial high-speed aircraft of the near future. Exposure at these altitudes depends critically on the types of remaining fragments after these collisions. Presently, cross-section data are insufficient for exposure estimates without attendant uncertainty. Two limiting physical processes bracket the contributions from nuclear collision events: (1) extreme peripheral collisions where a single nucleon is removed from the ion projectile on collision and (2) extreme central collisions in which the projectile ion fully dissociates into nucleonic constituents (the latter approximation is that used in current environmental models (refs. 8, 10, 22, and 27)). The calculated integral LET contributions from charged particles to dose equivalent at 80 000 ft for these limits are shown in figure 7. Also shown in the figure are the nominal values from the current LaRC database. The uncertainty in nuclear collision cross sections could result in uncertainty in contributions to dose equivalent for LET values above 10 keV/μm between 25 to 70 percent. Clearly, this is a serious limitation in current environmental models which yield results near the lower limit. Comparison with atmospheric air shower data measured by Webber and Ormes (ref. 52) shows that the environment represented as a calculation using the midpoint between nominal cross sections and the extreme peripheral values yields a slightly conservative estimate of the atmospheric environment as shown in figure 8. Present atmospheric exposure models (refs. 12, 14, 22, and 27) greatly underestimate the effects of these high-LET multiply-charged ion components.

Total exposure. Based on this discussion, we now estimate the range of exposures in flight at high latitudes during solar minimum. The tissue dose D is taken from the ion chamber data and calculated neutron dose and is assumed within 15 percent. The quality factors of gamma rays, electrons, and muons are taken as unity. The pion quality factor is assumed on the order of 2 and the estimate is taken from reference 45 as shown in table 4. The neutron contribution for $(\overline{Q}_n - 1)D_n$ is calculated from the neutron flux as given in reference 8. The remaining contributions are estimated by extrapolating the measurements of Webber et al. (ref. 52) by using the HZETRN code (a galactic cosmic ray transport code, ref. 53) with the results shown in figure 8 and table 4 and applying the uncertainty range associated with figure 7. As can be seen from table 4, the uncertainty in the neutron flux is very important at supersonic altitudes whereas uncertainty in the HZE flux dominates at hypersonic altitudes.

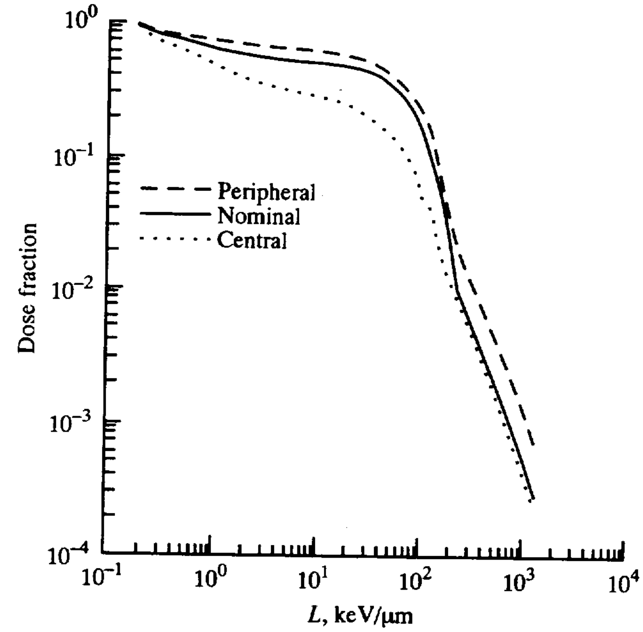


Figure 7. Dose equivalent fraction at 80 000 ft from greater LET values (polar region at solar minimum).

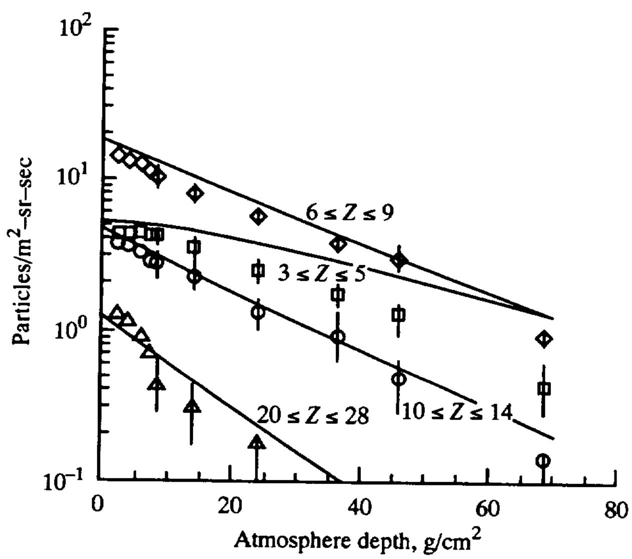


Figure 8. Vertical ion flux in upper stratosphere measured by Webber and Ormes (ref. 52) and present conservative model.

Table 4. Background Biological Exposure Components at High-Speed Altitudes in Polar Regions During Solar Minimum (1977)

Component	60 000 ft	70 000 ft	80 000 ft	100 000 ft
$\dot{D}$, μGy-hr^{-1}	5.9–7.8	6.9–9.1	7.4–9.7	7.4–9.8
$(\overline{Q}_i - 1)\dot{D}_i$:				
Subnuclear, μSv-hr^{-1}	≈0.01	≈0.01	≈0.01	
Neutrons, μSv-hr^{-1}	4.5–18.0	5.0–20.0	5.1–20.2	2.1–8.4
$Z = 1$, μSv-hr^{-1}	≈1.5	≈1.8	≈2.0	≈2.5
$Z = 2$, μSv-hr^{-1}	≈2.4	≈2.6	≈2.8	≈3.1
$Z > 2$, μSv-hr^{-1}	0.2–0.6	0.6–1.7	1.3–3.8	9.6–12.7

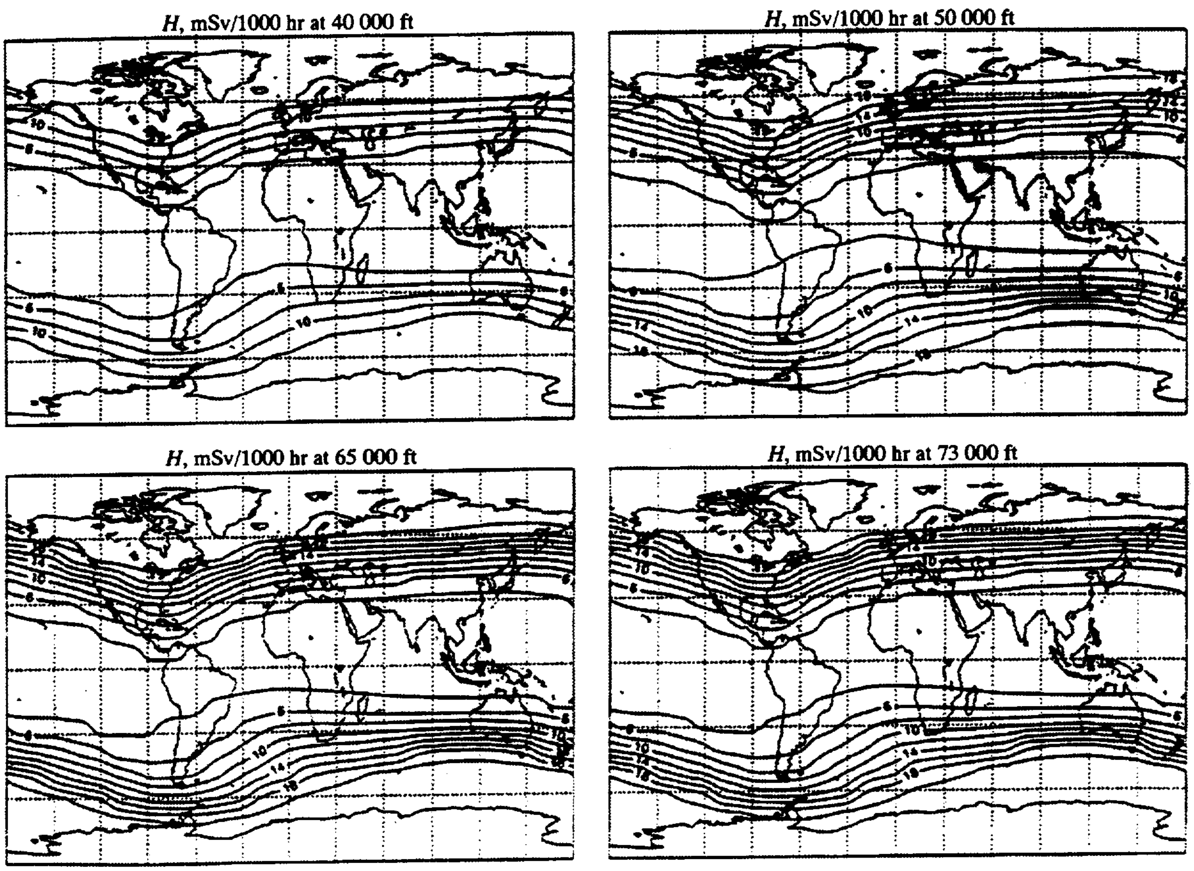


Figure 9. Background exposure levels in upper atmosphere at solar minimum.

As we discuss in the next section, the dose equivalent results based on quality factors are underestimates of the neutron exposure since higher weighting factors are recommended for neutron equivalent dose as opposed to dose equivalent as the standard in protection practice (ref. 6). The appropriate weighting factors for multiply-charged ions are unclear, but the importance of their contribution to dose equivalent is evident from table 4. Clearly, the major share of the dose equivalent is from radiation of high LET for which there is little or no human experience (ref. 18).

The values for total dose equivalent (in free air which we refer to as "exposure") for 1000 hr of flight are shown in figure 9 for solar minimum conditions. These are the maximum background exposure conditions. The variation of background exposure over the solar cycle is shown in figure 10. The radiation levels may vary over the solar cycle by as much as a factor of 2 in polar regions but vary only by 20 percent near the equator. Greater solar cycle variation is seen at high-speed operational altitudes than at subsonic altitudes.

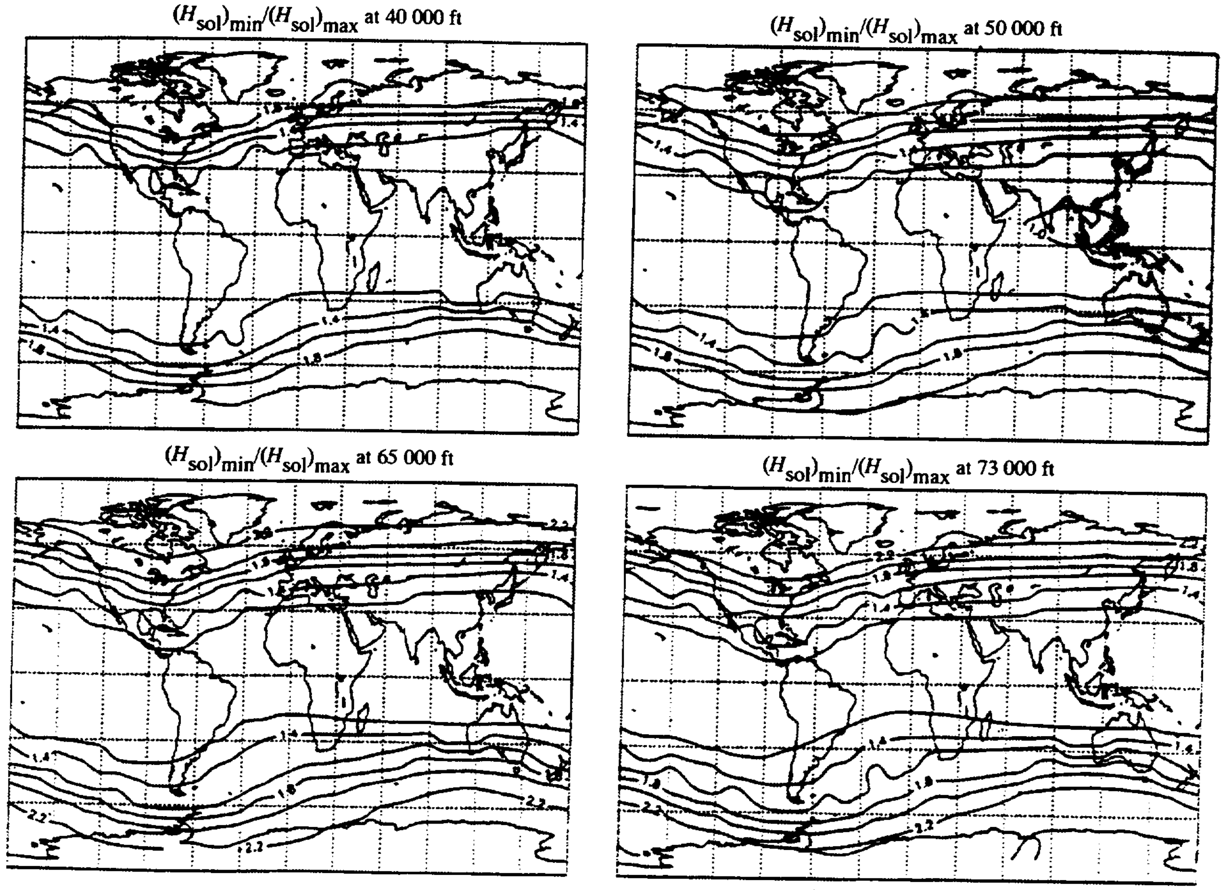


Figure 10. Maximum solar modulation ratio in atmospheric radiation levels.

According to current atmospheric radiation models (refs. 22 and 27), the main exposure from high-LET components is from neutrons produced in abundance through nuclear reactions of galactic cosmic rays (ref. 8). This is clearly true for exposures in the altitude range from 60 000 to 80 000 ft as seen in table 4 where various radiation components are displayed. From table 4, large uncertainties in the neutron spectral flux clearly leave the total exposure uncertain by a large factor. Other high-LET components are uncertain by about a factor of 2 because of uncertainty in nuclear fragmentation cross sections as shown in table 4. At higher altitudes above 80 000 ft, the multiply-charged ions dominate the exposures. There are no current environmental models representing these exposure fields.

Transient Exposures

Solar flares are associated with the magnetic irregularities in the solar surface (sunspots). During some solar flares, energetic particles are emitted with sufficient energy (greater than 100 MeV) such that their interactions in the atmosphere of the Earth produce many neutrons and other biologically damaging components (ref. 8) which penetrate deep into the atmosphere of the Earth. Measurements of fast neutron flux and tissue ionization were made in two flights with an RB-57F (an older Air Force supersonic airplane) during the solar event of March 30–31, 1969 (ref. 8). The dose equivalent increase inferred from the measurements at 65 000 ft was 13 μSv/hr above background at altitude (nearly doubling the dose equivalent rate over background levels), whereas ground level neutron monitors showed only a 5-percent increase above the background neutron count rate at the Deep River Neutron Monitor station (fig. 11). We may use this measurement in which the ratio of increase of background dose equivalent rate at an altitude of 65 000 ft is about 20 times greater than the increase of background neutron monitor count rate at ground level observed for

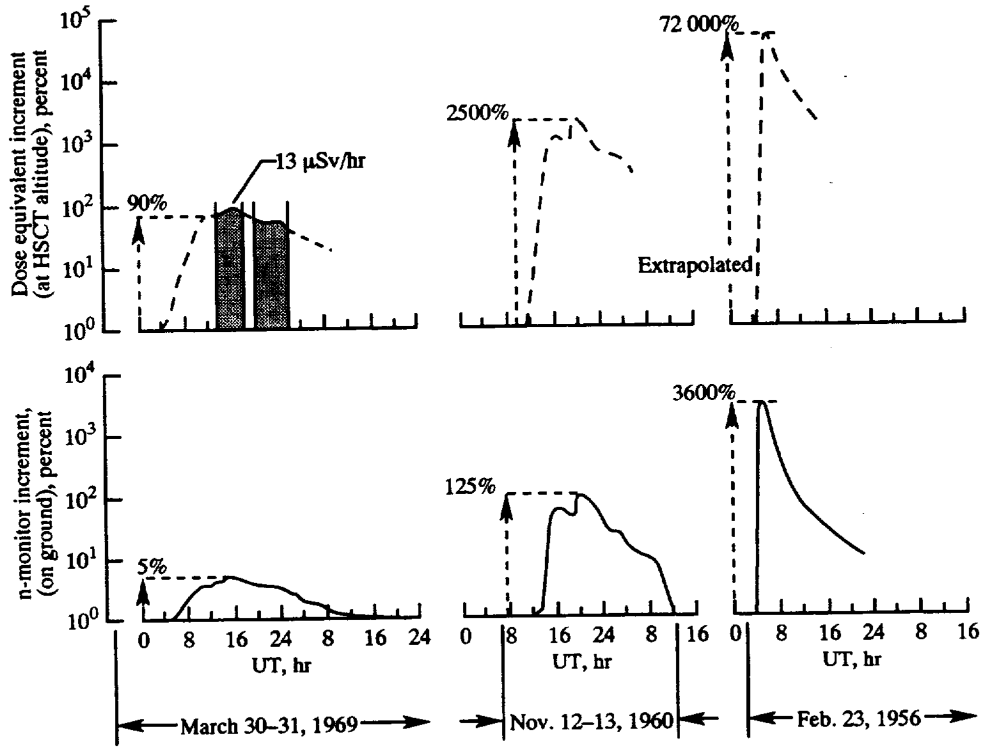


Figure 11. Energetic solar events measured on ground and at HSCT altitudes.

March 1969 to estimate the exposures at 65 000 ft for other much larger ground-level events which have been observed by ground-level neutron monitors for which corresponding high-altitude measurements are not available. For example, the November 1960 and February 1956 events are shown in figure 11. If we scale the ground-level increase according to the March 1969 measurements, large exposures can occur over a period of a few to several hours at high altitudes. The equivalent exposure of several years of the crew at background levels could be received in a few hours at 65 000 ft during such events. Even higher exposures would be encountered at higher altitudes.

Although the energy spectra of the particle fluxes of the February 1956 event are not exactly known, an upper and lower bound has been established (ref. 8) for the event maximum from limited balloon measurements and neutron monitor data at several locations. These spectra have been used as input to high-energy transport codes (ref. 8) at the LaRC and ORNL (HETC, a high-energy transport code, ref. 54) and are shown in figure 12. It is important to note that the 72 000-percent increase for the February 1956 event corresponds to approximately 10 mSv/hr at 65 000 ft (58 g/cm^2 depth) in the atmosphere near the lower limit estimate shown in figure 12.

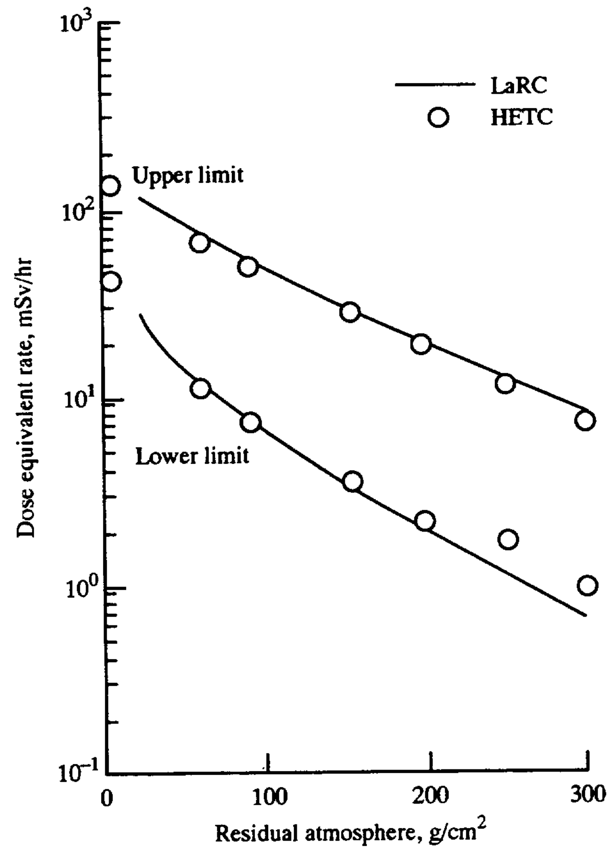


Figure 12. Calculated upper and lower limits for dose rate of February 1956 solar event.

Exposure Estimates

The exposures for three flight regimes—subsonic flight, near-term supersonic flight, and long-term hypersonic flight—are considered. Both national and international air routes are well established for subsonic operations. Supersonic operations will mainly compete in the international flight market with subsonic flights limited to airspace over large bodies of water (ref. 55). Hypersonic operations near Mach 5 appear feasible (ref. 56) and will mainly operate on international flights over water.

The projected routes (ref. 55) for a Mach 2.4 HSCT are shown in figure 13. Note that the fuel usage is a rough indicator of the number of annual flights. When comparing figure 13 with the geographic distribution of exposure rates in figure 9, one sees that the main Atlantic routes pass through a portion of the northern polar region defined as the plateau in dose rate around the north pole. The same holds for popular flights from the U.S. and Europe to Tokyo. Even flights from Los Angeles to Tokyo pass near the edge of the polar region at its nearest approach to Alaska. We consider three flight paths indicated as both subsonic and supersonic routes (ref. 55) for analysis: (1) London to New York (LHR–NYC) which is in the heart of the Atlantic corridor, (2) London to Anchorage (LHR–ANC) which is a connecting flight to Tokyo, and (3) Frankfurt to Tokyo (FRA–NRT) with a stop in Helsinki. We have evaluated the solar minimum exposures averaged along these routes for present day subsonic flight at 39 000 ft and supersonic flight over waterways at 65 000 ft (restricted to 31 000 ft over land). The nominal exposures are calculated by using current environmental models (ref. 27). The uncertainties shown in table 4 are applied to the models to estimate an upper and lower limit. The exposure rates are shown along the three routes in figure 14. The sudden rise and fall in exposure rates near 1500 and 5200 miles in figure 14(f) is due to the change in altitude at the coast line. The average exposure rates are used to evaluate the annual crew exposure in figure 15 for different assumed number of block hours (time from when

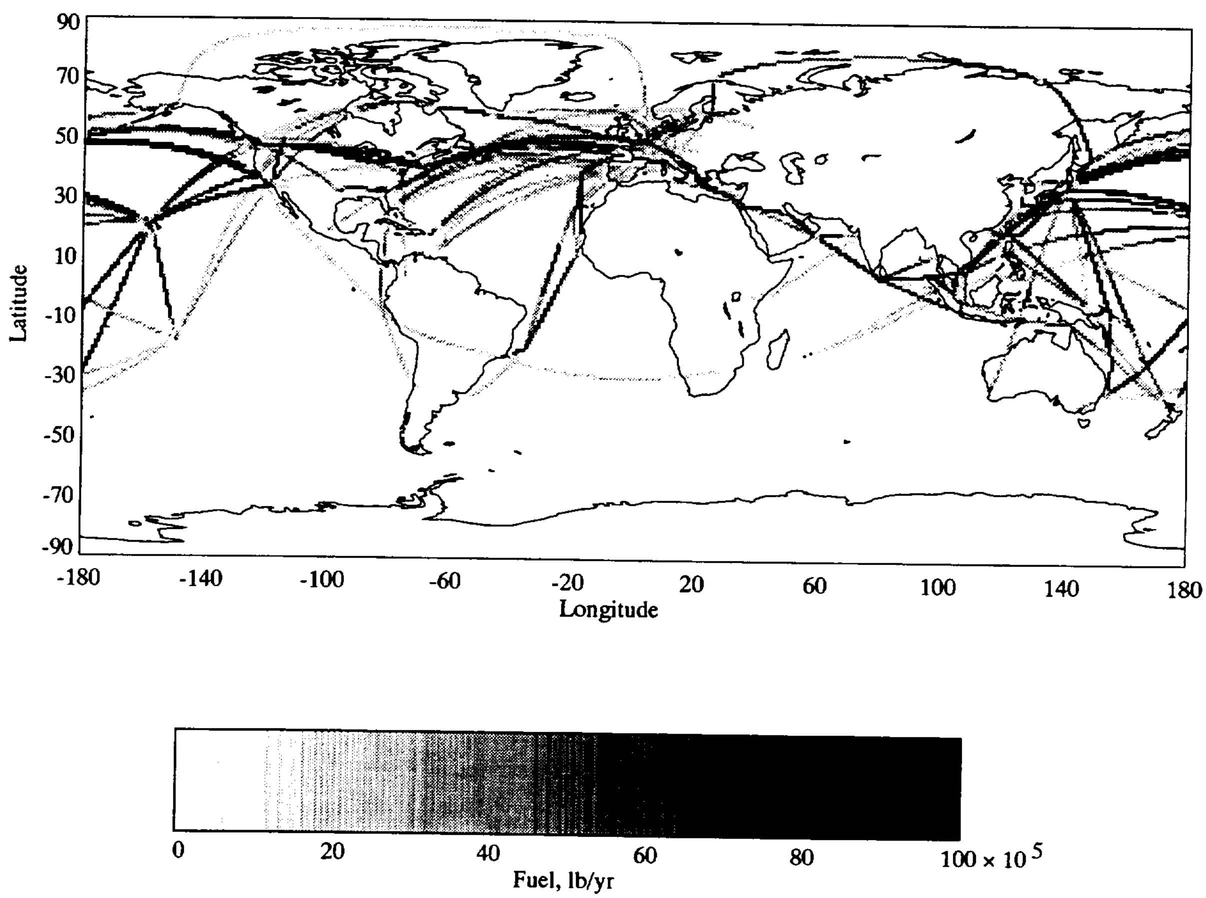
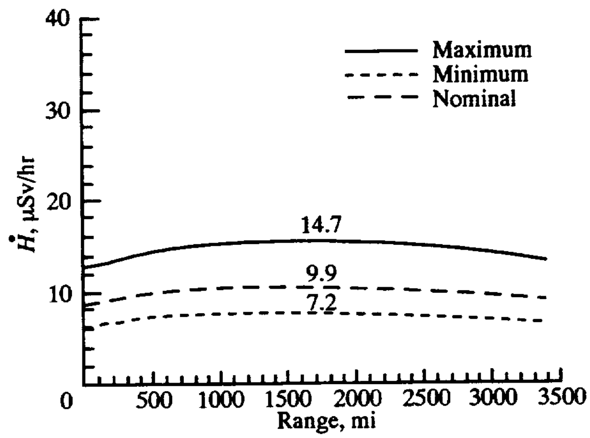
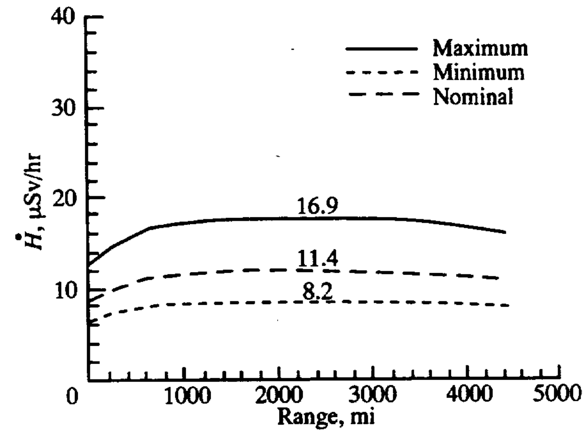


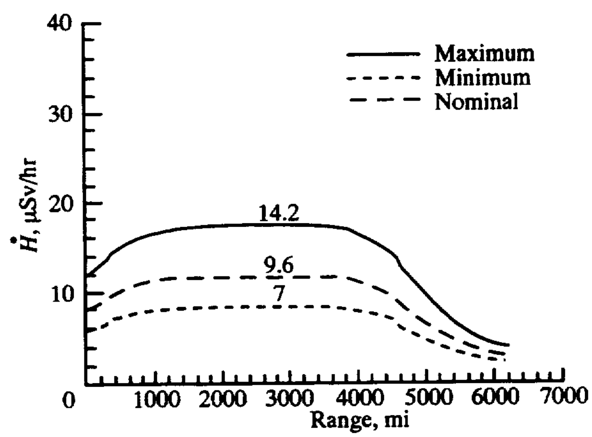
Figure 13. Projected air routes of commercial HSCT operations in 2015 at Mach 2.4.



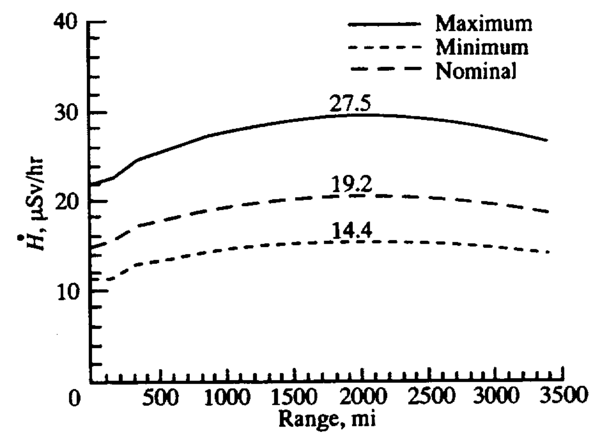
(a) Subsonic flight from London to New York.



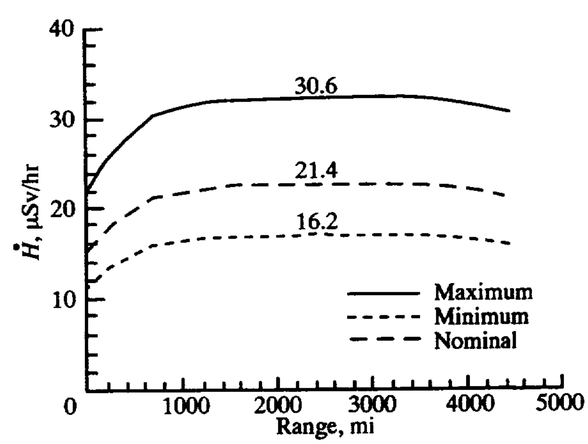
(b) Subsonic flight from London to Anchorage.



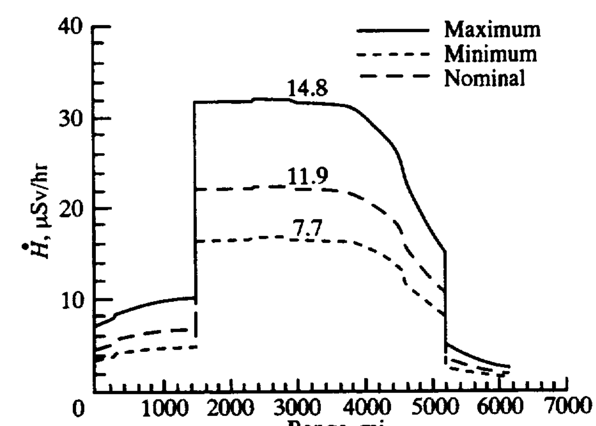
(c) Subsonic flight from Frankfurt to Tokyo.



(d) Supersonic flight ($M = 2.4$) from London to New York.



(e) Supersonic flight ($M = 2.4$) from London to Anchorage.



(f) Supersonic flight ($M = 2.4$) from Frankfurt to Tokyo.

Figure 14. The exposure rates along three flight paths for present day commercial operations and HSCT at Mach 2.4.

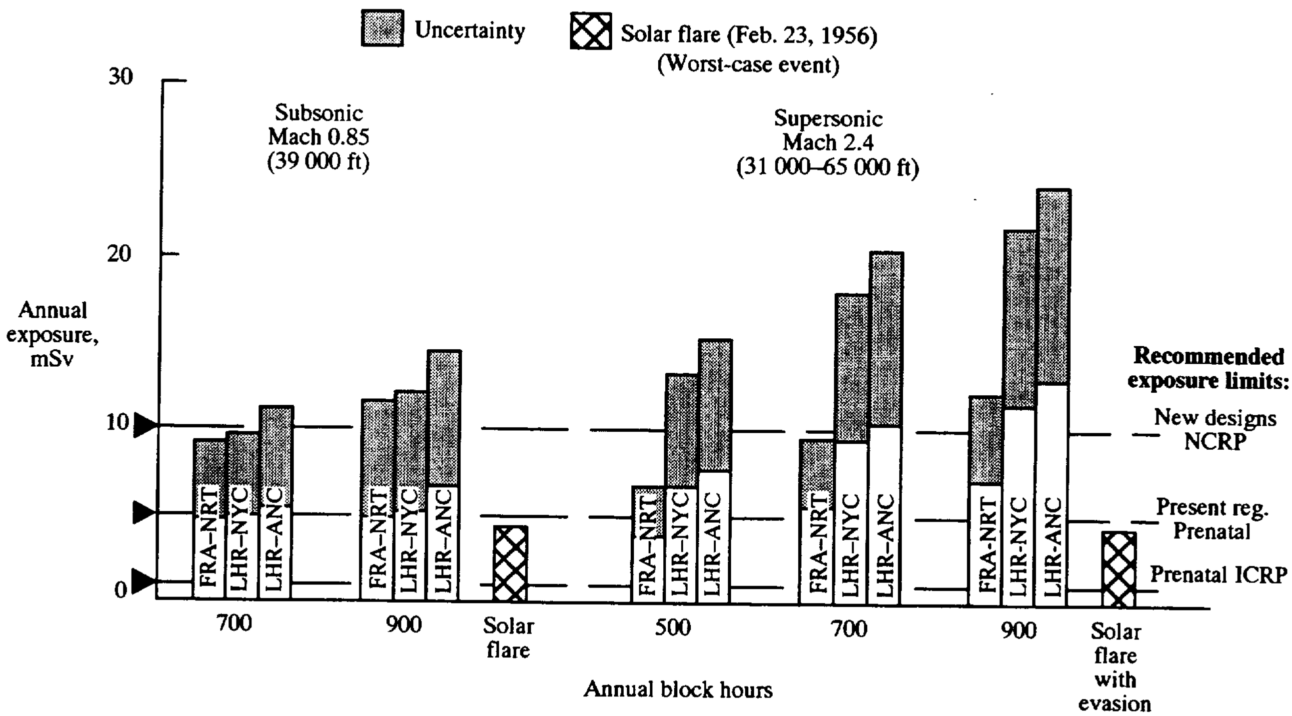


Figure 15. Annual crew exposures for subsonic and Mach 2.4 flights along specific air routes for assumed number of block hours.

wheels are unblocked for the roll back from the gate to reblocking on arrival). Also shown in figure 15 are the solar flare exposures for the February 1956 event if it occurred while the aircraft was in the polar region and a timely descent to 35 000 ft was made.

The three routes chosen for analysis in figure 15 pass through the north magnetic polar cap and are among the most exposed routes. The London to New York route is one of the most traveled international flights in the world. The exposures depend on the number of block hours with 700 to 900 hr as a typical range for present day subsonic flights. The block hours of 500 to 900 were assumed for the Mach 2.4 operation. The uncertainty in exposure estimates is in accordance with the environmental uncertainty in table 4. The design occupational exposure limit recommended by NCRP for new operations or procedures of 10 mSv (ref. 5) is shown. Such a limit may be exceeded, depending on the number of block hours flown in the year of solar minimum. Also shown is the recommended prenatal exposure limit of the ICRP (ref. 6). If the ICRP limit for prenatal exposure is accepted as a regulatory standard then an appropriate policy needs to be implemented. The limits are not a goal for the design but rather a limit above which some positive action to reduce exposure is required. The design goal with respect to regulatory requirements is to keep exposures as low as reasonably achievable (ALARA principal). An issue with respect to the environmental impact statement for the HSCT will be the implementation of ALARA into the aircraft design and operation.

The higher exposure levels in supersonic flight for the same number of block hours result from the higher average exposure rates at higher altitudes. In both supersonic and present day subsonic operations, the exposures are nearly equal to or possibly greater than the "new design limit" recommended by NCRP. Special consideration needs to be given to the prenatal exposures since exposure limits are easily exceeded. Pregnant crew rotation or restriction to less exposed routes needs to be examined as an option. "For example, one of the safety measures may be a recommendation for women to refrain from flying on high-altitude airliners during the initial weeks of pregnancy in order to exclude possible radiation damage of embryo cells during the organogenesis period." (ref. 57).

The exposures for frequent flyers with 10 round trips assumed annually are shown in figure 16. The higher exposure for subsonic flights along the same route results from the longer flight time; the business class frequent flyer would be substantially less exposed on the Mach 2.4 HSCT. Clearly, 10 trips or less would be allowable during the period of gestation. The exact number of allowable trips before 1 mSv is exceeded cannot be determined without reduction of the uncertainty in the exposure rates. The 1-mSv limit is also the allowable limit for the traveling public

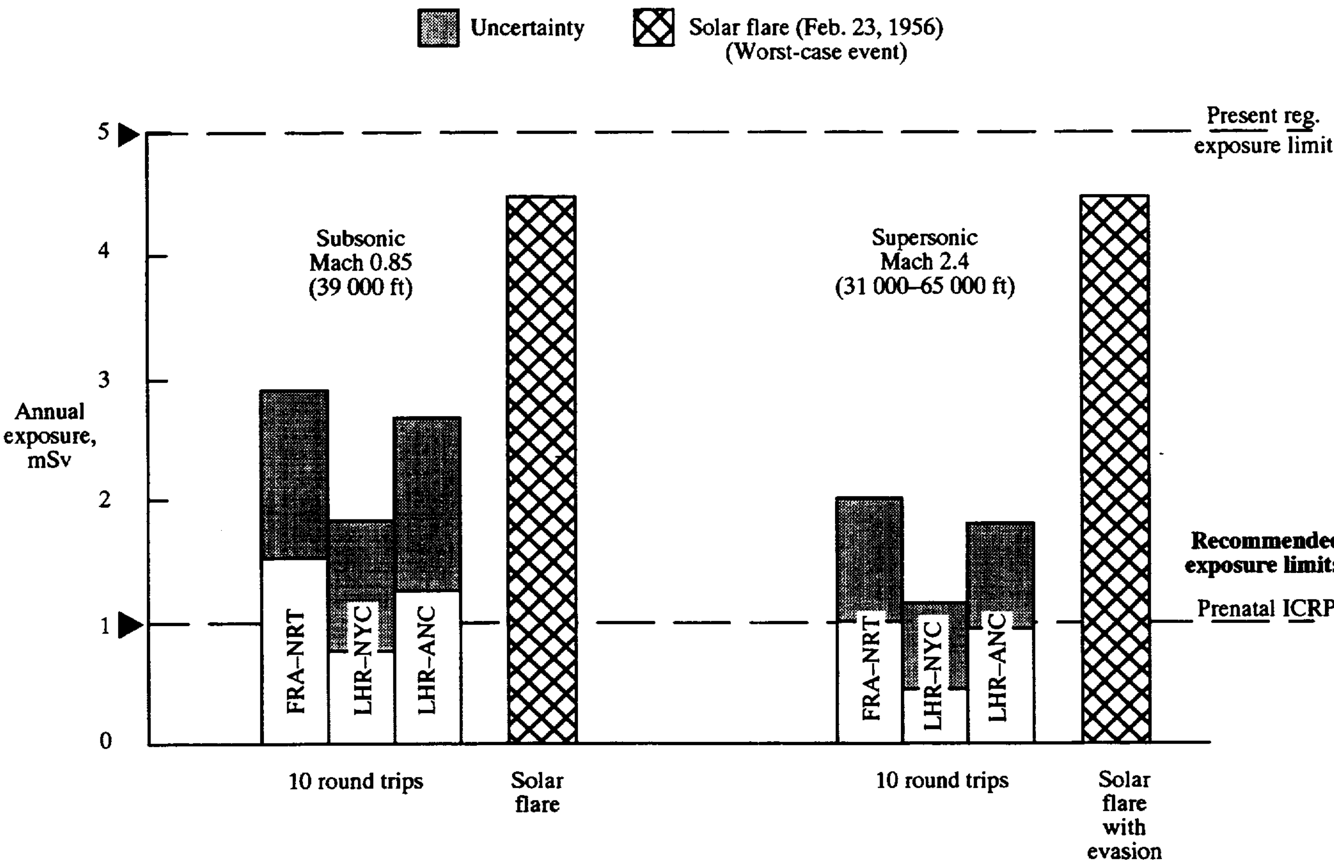


Figure 16. Frequent flyer annual exposure for subsonic and Mach 2.4 flights along specific air routes for 10 round trips.

(ref. 6), and the impact of the frequency with which they fly cannot be adequately addressed without reduction of the associated environmental uncertainties. In the event of a large high-energy solar flare such as the one that occurred in February 1956, large exposures can occur in passage through the polar region. These events are very rare, but means of protecting passengers in such an event requires adequate monitoring and sufficient aircraft capability to evade the exposure.

Crew exposures are evaluated for Mach 3.2 and Mach 5 for the three routes and shown in figure 17. The trend in increasing dose equivalent rate with increasing altitude is clearly seen as increased exposure for a fixed number of block hours. The lower uncertainty in exposures is due to the lesser importance of atmospheric neutrons (table 4). The frequent flyer exposures (10 round trips per year) shown in figure 18 continue to decrease with increasing Mach number because of the shorter exposure periods.

There are several contexts in which high-altitude exposures could be viewed. One context is to compare these exposures with those of other radiation workers. The average exposure of a radiation worker in the nuclear industry is about 2 mSv/yr (ref. 36, p. 153). The most exposed radiation worker subgroup in the nuclear industry is the fuel cycle workers who currently receive 6 mSv/yr as a subgroup average (ref. 36, p. 153). The average astronaut career exposure is 20 mSv, yielding an annual average of 4 mSv with a 5-year career assumed (ref. 58). With the data in figure 15 and table 4, the background exposure of the stratospheric air crew would be on the order of 7 to 15 mSv during solar minimum along northern routes at the higher altitudes, nearly double the annual exposure of the fuel cycle workers in the nuclear industry. Should the crew encounter a solar event like that of February 1956 and take no action to reduce exposure, the exposure of that flight could be as high as $\approx$60 mSv or more for supersonic and hypersonic flight. The passengers would likewise be exposed at these levels for a single flight in a February 1956 event. Otherwise, passengers would receive no more than 0.16 mSv per round trip (8 hr). A business traveler or diplomatic courier may make 1 trip/wk along high-latitude routes and receive exposures similar to the crew. These results are summarized in table 5.

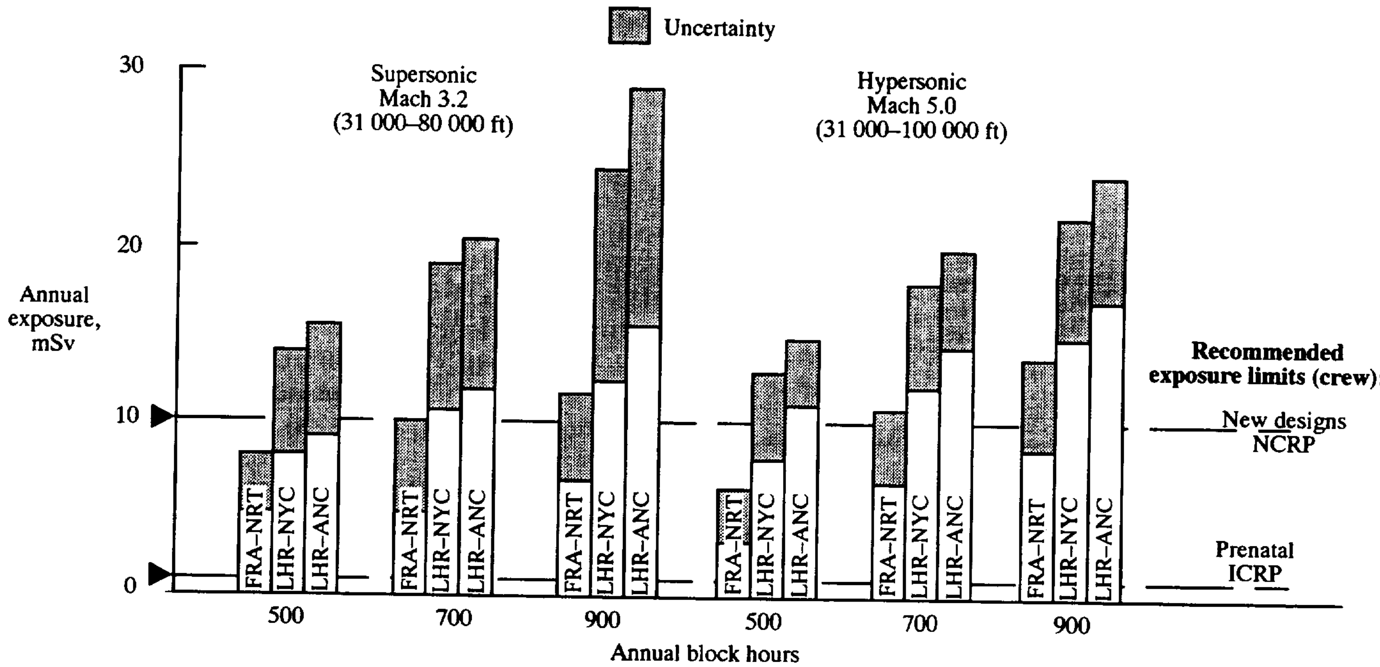


Figure 17. Annual crew exposures for Mach 3.2 and 5.0 flights along specific air routes for assumed number of block hours.

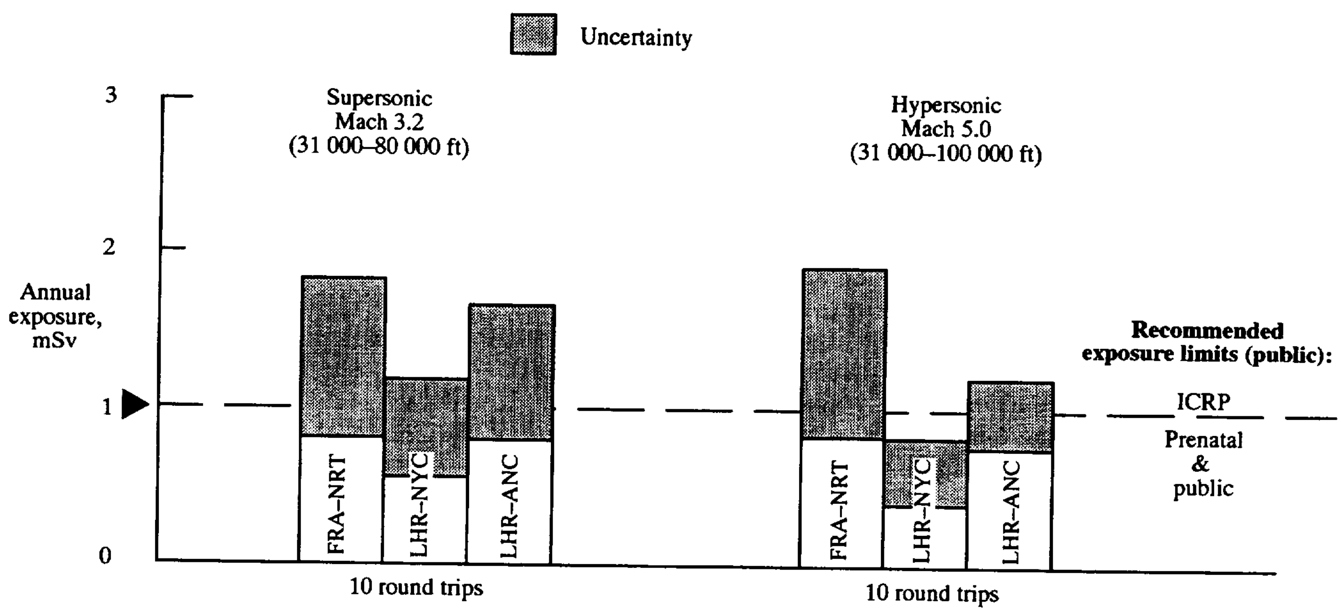


Figure 18. Frequent flyer annual exposure for Mach 3.2 and 5.0 flights along specific air routes for 10 round trips.

Comparison With Occupationally Exposed

Clearly, the average air crew member may be exposed to a much higher level of radiation than the average fuel cycle worker in the nuclear industry (although a few workers in the nuclear industry will have exposures near 50 mSv/yr) or the average astronaut. The crew and passengers may receive even greater exposures in the event of a large solar flare. Most passengers may be only nominally exposed to background levels on a single round trip (on the order of 0.16 mSv), but they could receive high exposures on a single flight during a large solar flare. The background exposures of frequent flyers also could exceed the average exposures obtained in the nuclear industry.

Table 5. Occupational and High-Latitude Exposure Estimates

Exposure condition	Exposure, mSv	
	Annual	Exceptional[a] (February 1956)
Occupational:		
Fuel cycle workers	6	
All workers	2	
Astronaut	[b]4	≈1000
Air crew (500 hr):		
Mach 0.85	≈7	≈5
Mach 2.4	≈10	≈60
Mach 3.2	≈13	≈100
Mach 5.0	≈15	≈130
Passengers (Mach 2.4):		
1 round trip/yr	≈0.16	≈60
1 round trip/wk	≈8	≈60

[a]No attempt made to evade exposure.

[b]With 5-yr career assumed.

Comparison With Present Exposure Standards

A second context from which the exposures can be viewed is according to safety standards used for the protection of workers and the public from ionizing-radiation sources. Present standards (ref. 37) within the United States (table 1, first column) require occupational exposures to be less than 50 mSv in any year except in the event of pregnancy for which 5 mSv only are allowed in the period of gestation. In any given year, a planned or unplanned emergency can allow a higher exposure provided that an accumulation of dose does not exceed the exposure as given by the formula $[0.05 \times (\text{Age} - 18)]$ Sv, there is no pregnancy, and a dose rate of 30 mSv/quarter is not exceeded. The most difficult exposure standards for the crew to be met is the 5-mSv limit in the event of pregnancy and the 30-mSv limit for any quarter year. The limits for pregnancy can be exceeded by background levels in about 31 round trips (approximately 6 mo) and by a solar flare in 1 day. The crew would never fit within the exposure standards for the general public (table 1). The less frequently flying passenger could make 6 round trips per year without exceeding the present 1-mSv limit for the public unless a large solar event occurs. (The general public would be allowed up to 5 mSv in an emergency.)

The main health concern in the event of a large solar flare is for pregnant crew members and passengers. Clearly, in some cases the exposures could be in excess of currently accepted exposure standards. Strictly speaking, no current regulations for aircraft operations exist and we have merely referred to standards of safe practice in radiation-related human endeavors.

Comparison With Proposed Standards

Since the standards presently in force were established in the United States (ref. 37), new epidemiological studies especially of the A-bomb survivors and a reevaluation of the A-bomb dosimetry have been made. The result of the latest dosimetry reduces the contributions from neutron exposures in the A-bomb data to near negligible. Thus, the A-bomb exposures are now estimated to be mainly from gamma rays. The latest resulting health risk coefficients are given by the UNSCEAR report (ref. 16) and BEIR V report (ref. 17). New standards for the United States have been proposed (refs. 5 and 38) and are shown in table 1. The crew would be limited to a maximum annual exposure of 50 mSv which could be exceeded in the year of a large solar event, but the problem of exposure during pregnancy remains. The general public could be limited to 6 round trips per year, and the solar flare problem remains. Such reduced standards, if adopted, could have a major impact on protection practices of high-altitude and subsonic aircraft (refs. 4 and 27). The 0.5-mSv limit for any month recommended by the NCRP (ref. 5) would be particularly limiting for pregnant crew members and some passengers (such a limit is reached in only 3 round trips). The ability to do meaningful scheduling to less exposed routes depends on decreasing the present environmental exposure uncertainty and record keeping of crew exposures.

On the basis of the UNSCEAR report, the International Commission on Radiological Protection (ICRP) has proposed new protection standards (ref. 6). The ICRP recommended 1-mSv *in utero* limit during the period of gestation which could be reached in only 6 round trips (within a few weeks for the crew); this will provide a major impact on female crew members. Indeed, such an exposure limit could be exceeded even before the pregnancy is confirmed and would negatively impact individual careers.

Associated Health Risks

Aside from the legal and possible regulatory implications of exposing the public and crew to potentially high levels of radiation (under the NRC there are reporting requirements), the primary health concern is exposure of pregnant occupants in high-altitude aircraft. The risk coefficient for severe mental retardation of an unborn child is 40 percent/Sv for exposures in the first 8–16 weeks (ref. 6, p. 147) and for childhood leukemia or solid tumor incidence is about 2 percent/Sv for exposure during the gestation period (ref. 17, p. 149). At any given time at cruise altitude, there may be approximately 180 pregnant women of which 40 are in their first 8–16 weeks of gestation. (See appendix.) The estimated risk of mental retardation due to an exposure of 60 mSv is 2.4 percent compared with a natural risk of 0.4 percent (ref. 59), and the estimated risk of childhood leukemia is 0.12 percent. The risk to the unborn child of an airline crew member is somewhat higher than for regular passengers because of background exposure.

The *estimated* health risks of the crew on the basis of exposure are small (ref. 22). Studies of air crews of the Canadian airlines reveal substantially increased risks of several types of cancers (ref. 60). It is not known whether the cause of these cancers is due to ionizing radiation or other agents but is conceivably related to uncertainty in the health risk from the unique radiations in the upper atmosphere (ref. 60). Astronaut health risks are expected to be an order of magnitude smaller than the air crew, and observed astronaut radiation-related health risks are, in fact, small (ref. 61).

A large fraction of the transient exposure is from high-energy neutrons produced in the overlaying atmosphere. Actual response may be different than those estimated, but no human data are available for such exposures. The problem of solar flares remains as a critical issue.

Exposure Abatement

From the previous discussion, it is clear that high exposures can occur, but the associated risk of those exposures is uncertain since most of the exposure is from high-LET components, for which little or no human or animal exposure data are available on which to establish exposure risks and limits. Even the levels of the exposure components are uncertain because there are insufficient measurements of the high-energy neutrons and the multiply-charged ions and presently available computational models are not sufficiently accurate because of a lack of nuclear cross-section data. Yet, an exposure abatement program must first provide a means of evaluating risk from all the important environmental components and evaluate the effects on those environmental components by altering the material arrangement, chemical composition of the aircraft structure and components, and possibly the operating altitude and route, depending on solar activity. For example, a variation of 10 to 30 percent was measured aboard present day commercial transports (ref. 62). To take advantage of design and operational options, one must understand the inherent health risk contribution of each radiation component and the important design and all operation parameters affecting those components. As was noted in the previous section, important environmental components have not been adequately measured and their biological effects are not well understood (refs. 18 and 63); therefore, serious uncertainty is left in our ability to control the magnitude and effects of exposure based on our current state of knowledge.

This discussion raises a number of issues that must be resolved in the three categories of radiobiology, environmental physics, and engineering design. Although these issues are now discussed separately, the issues are interconnected.

Radiobiological Issues

Most of our knowledge on human radiation risk is from the exposure data of the nuclear weapons of World War II. The primary data on fatal cancer risk and mental retardation for prenatal exposure are from analysis of those exposed to the A-bomb (ref. 17). Data on childhood leukemia from prenatal exposure are mainly from diagnostic X-ray data (ref. 35) and are consistent with A-bomb exposure data (ref. 17). Uncertainty arises in applying these acute exposure risk data to individuals exposed chronically over their career; none of the available human exposure data contain significant contributions from neutron or multiply-charged ions, the effects of which must be estimated from other sources by using model biological systems. These issues and the resultant uncertainty were discussed in previous sections. A principal concern in aircraft exposure is for developmental injury due to prenatal exposure for which quality factors are not even defined (refs. 5 and 6).

Prenatal Exposure

Embryonic lethality in animal experiments occurs at low doses ($\approx$0.1 Gy) before and immediately after implantation (refs. 16 and 17). Although lethality occurs at higher doses at later stages of pregnancy, sensitivity at a particular time in gestation is not known. Further studies are being prepared in which early lethality will be studied in present commercial airline operations (ref. 31).

Malformations characteristic of the stage of organogenesis, especially in the periods of cell proliferation and organization, result from cell killing (ref. 17) or altered gene expression (ref. 40). Modification of brain structures resulting in radiation-induced mental retardation in humans is a known risk at the time of cortex formation (very sensitive for 8–16 weeks, reduced sensitivity for 16–25 weeks, and greatly reduced sensitivity after 25 weeks). Intelligence quotient losses of 30 points/Sv in the most sensitive period are observed (ref. 6). Competition with lethality may be in part the cause for reduced sensitivity prior to 8 weeks, but such a competition related effect is not clear (ref. 6).

Quality factors for developmental injury are not yet defined. If cell killing is the primary injury mechanism then quality factors on the order of 2 to 20 in the high-LET region would appear appropriate from mammalian cell culture experiments (refs. 40 and 64). On the other hand, if damage to the genome is the effective criterion, then genomic instability, chromosome damage, or sister chromatid exchange may be more appropriate for which very large (perhaps infinite) RBE's have been measured (refs. 65 through 67). Recent studies with mouse embryo find low-energy alpha particles to be extremely damaging to developing hemopoiesis (ref. 40) and very large RBE's on the order of 250 to 360 may be appropriate. An argument may be given that the latter RBE's may be appropriate as follows. The damage to hemopoiesis results from the disorganization of the stroma which shapes and controls the stem cell populations and not direct damage to the stem population. The organization of the stroma is affected by growth control factors which are functions of gene expression. It is this altered gene expression which is likely the main disorganizational factor in mental retardation and not cell killing. Recent studies on chick embryo neural development with X-ray exposures show significant alteration in the distribution of neurites (ref. 68).

Childhood leukemia induction is most apparent in prenatal X-ray exposures, but results are consistent with A-bomb exposures within the statistical uncertainty (ref. 6). The induction rate seems independent of the time of exposure during gestation, and the risk of fatal childhood cancer is estimated to be 2.6×10^{-2}/Sv (ref. 17). The quality factor for stochastic processes would be appropriate. However, the use of DREF ≈ 2 may be inappropriate in that high-LET exposures show an enhancement of cell transformation (ref. 69) and life shortening in mice (inverse dose rate effect, ref. 70). Clearly, present radiation protection practice may significantly underestimate the risk to the developing embryo.

Neutron Exposures

The risk associated with gamma ray exposure is relatively well-defined and is the primary source of current radiation protection practice. Biological experiments are used to estimate relative biological effectiveness of different radiation types on which the definition of quality factor rests. Such an extrapolation depends on the existence of appropriate experiments. The most common neutron exposures utilize neutron beams generated by fission reactions with some degree of moderation. The fission spectrum of ^{235}U is shown in figure 19 along with the histogram generated by the Monte Carlo calculations shown in figure 4. The contribution to neutron dose per energy decade at 70 000 ft shown as the dashed histogram in figure 4 is indicated by the histogram in figure 19. Clearly over half of the neutron exposure at 70 000 ft is from neutrons with energies above 10 MeV, which are not representative of the fission neutron spectrum. The only known representative ground-based neutron exposure facility is the white neutron source (WNS) at the Los Alamos National Laboratory for which the spectrum is also shown in figure 19 together with a calculation of the cosmic ray neutron spectrum. Unfortunately, there have been no systematic biological studies utilizing this facility for use in establishing risk estimates.

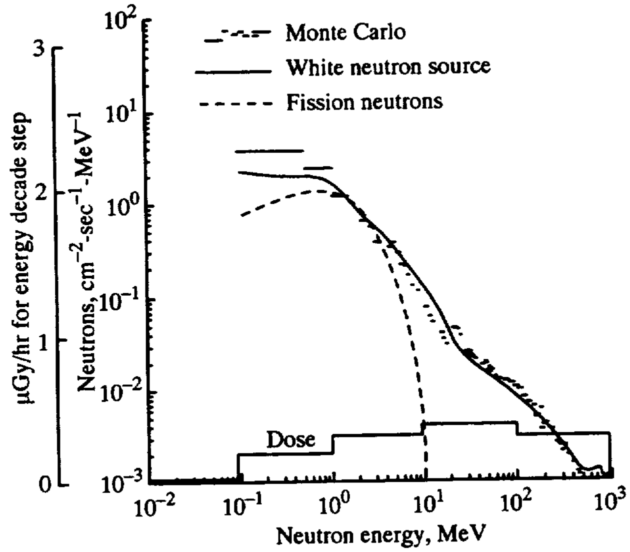


Figure 19. Calculated neutron spectrum at 70 000 ft and high latitudes near solar minimum (histogram) with typical fission neutron spectrum and 15° spectral distribution of white neutron source.

An interesting point with respect to high-energy neutron exposures is that the energy deposit is through nuclear reaction events of the more massive nuclei of the tissue system. The LET distribution of multiply-charged secondary products from 1-GeV neutron reactions is shown in figure 20. Also shown is the LET distribution of the ^{239}Pu alpha decay for

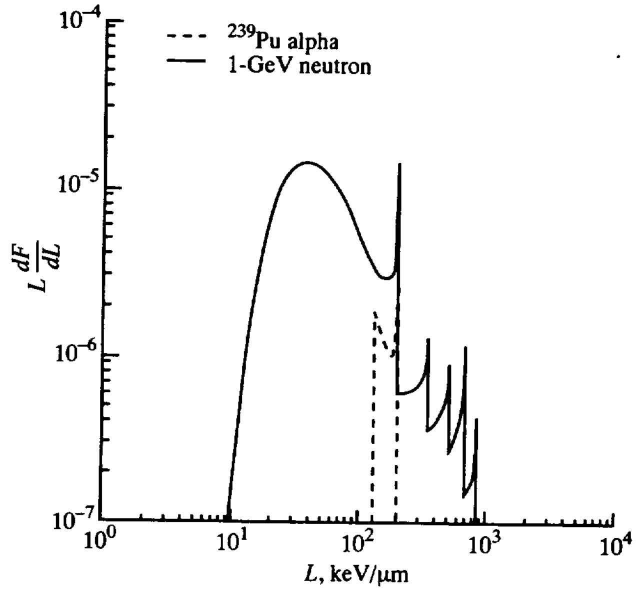


Figure 20. LET distribution produced by 1-GeV neutron in tissue along with ^{239}Pu alpha decay spectrum.

which large RBE's are observed for hemopoiesis. The importance of these high-LET nuclear events require better understanding.

Neutron RBE values have been measured (ref. 71) for 400 MeV and several biological end points. RBE values of 6 to 10 have been measured for lens opacification and spermatogonia survival. In the spermatogonia survival experiments, the RBE was found to increase with decreasing dose as $D^{-1/2}$ below 0.1-Gy exposures so that $(\mathrm{RBE})_M$ is not yet achieved. As yet, no such values of $(\mathrm{RBE})_M$ are available for the neutrons in the atmosphere but the large $(\mathrm{RBE})_M$ values in table 2 and the measurements of Bianchi et al. (ref. 71) clearly emphasize their potential importance in aircraft safety.

Multiply-Charged Ion Exposures

Our prior atmospheric radiation models did not include the multiply-charged ions. Risk estimates for these particles are problematic because insufficient data exist to determine the RBE's with which to extrapolate the gamma ray exposure data (ref. 36). Such ions may produce effects and associated end points for which gamma ray exposures are incapable (that is, RBE is effectively infinite). Such RBE values are found in cellular exposures in the measurement of sister chromatic exchanges in resting human lymphocytes irradiated with ^{238}Pu alpha particles (ref. 67) by the observation of abnormalities in stem cell colonies surviving similar alpha particle irradiations (ref. 65) and by the partial disintegration of chromosomes after irradiation with multiply-charged ion beams (ref. 66). Todd (ref. 72) has postulated that biological effects may occur at the tissue level by a single heavy ion traversal (ref. 72) for which there is no corresponding gamma ray effect.

These unusual features of multiply-charged ion exposures result from the characteristics of the energy deposited around their trajectories. The average dose distribution $\overline{D}(t)$ as a function of transverse distance t from the path of the ion (ref. 73) is shown for several 1 GeV/amu ions in figure 21. Clearly, the effects of proton exposures are dominated by those trajectories which pass through the cell nucleus. In distinction, the gold ions produce significant exposures far from their trajectory. We use the curves in figure 21 to estimate cell killing and neoplastic transformation (the first step in cancer formation) surrounding the particle trajectory as shown in figure 22. The probability of cell killing is taken as

$$P_d(t) = 1 - e^{-\overline{D}(t)/D_d}$$

where D_d (≈2.6 Gy) is the dose for which only 37 percent of the cells survive. The probability of a transformed cell being formed in a concentric cylindrical shell of radius t is taken as

$$P_T(t) = \frac{2t}{a}\left[1 - e^{\overline{D}(t)/D_t}\right]\left[1 - P_d(t)\right]$$

where a is the cell radius (here taken as 5 μm) and D_t (≈120 Gy) is the transformation sensitivity. Clearly, the lesion formed in the tissue system by relativistic gold ions will be a core of dead cells surrounded by a cylindrical shell of potentially transformed cells. An estimate of such a transformed cell being formed by the passage of relativistic gold is 10 percent/cm. As the tissue responds to healing in the central core, the growth activity in surrounding cells is likely to promote a transformed cell to a malignant phenotype. This is the essence of Todd's mechanism (ref. 72) which is peculiar to very heavy ion exposures. The heavier ions are quickly attenuated in the atmosphere but measurable numbers of secondary fragments penetrate to HSCT altitudes (fig. 8).

Since the population at risk in commercial air traffic spans all ages and the preborn, one must consider the effects of multiply-charged ion injury at all ages of development. Such cell-killing effects during organogenesis and development could conceivably lead to serious effects for which we now have no quantitative experience. Also cell mutation in the periphery of the tract was the basis of Todd's mechanism and such mutational events may have importance in

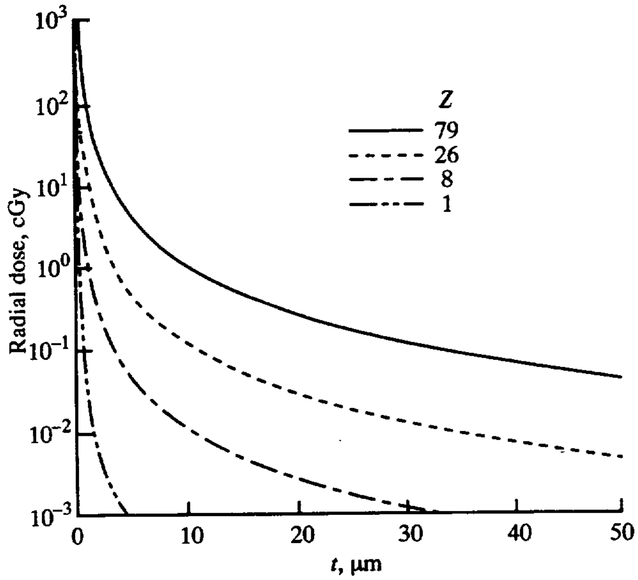


Figure 21. Radial dose distribution for several ions at energy of 1 GeV/amu.

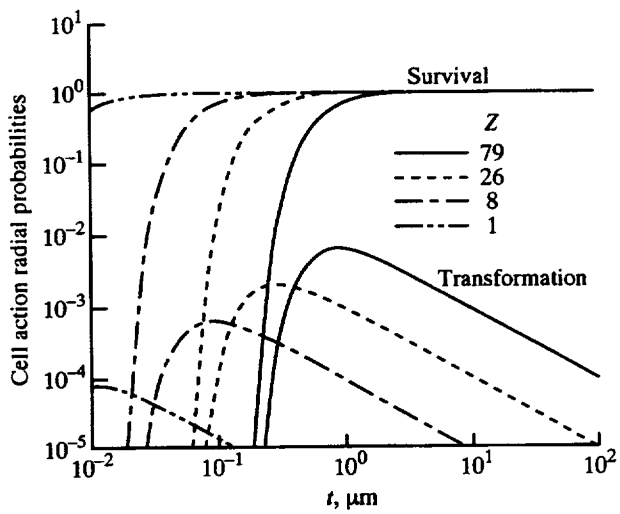


Figure 22. Cell action probabilities about several ion tracks at energy of 1 GeV/amu.

other tissues. For example, the prevalence of transmittable mutation events occurring in relativistic Fe exposures of mouse testes is 50 times higher than the direct hit rate; thus the importance of the energy distribution about the ion path is indicated (ref. 74).

Environmental Physics Issues

The exposure of the high-speed commercial air crew is high compared with other exposed groups (including the nuclear fuel cycle workers), and a significant fraction of the accepted exposure limits is achieved and possibly exceeded for pregnant crew members. For these reasons alone, improved environmental models must be developed for crew exposures. This is even more critical as proposed exposure limits and new methods for estimating biological risks (increased quality factor and radiation weighting factors) will further increase exposure estimates and make it more difficult to keep exposures within acceptable limits. This is especially true at the highest stratospheric altitudes, where significant exposures with multiply-charged ions occur. These added factors further emphasis the need for development of more accurate environmental models suitable for crew exposure estimates. In this section, the issues of better defining the physical radiation environment are discussed. In the present context, it is very important to emphasize the knowledge of the physical fields including spectral distribution and particle type experienced by the crew and passengers rather than the reduced quantities such as dose and dose equivalent which are derived from the application of quality factors or weighting factors because such biological weighting factors are being revised and will probably be further revised before supersonic and hypersonic aircraft go into operation.

High-Energy Neutrons

From the previous analysis, it is clear that the high-energy neutron fields are still not known and are very controversial (ref. 75) and that large uncertainties in the corresponding dose exist. Still, it is well established that the high-energy neutrons are an important contributing factor in the overall exposure. Therefore, a fundamental neutron measurement program is required, and an improved environmental model should be developed.

Multiply-Charged Ions

A survey of the multiply-charged ion data measured in the stratosphere is required to assess our current database of measured data in the upper atmosphere. These data will be used to evaluate current computation models for estimating this component. These particular components are in a rapid transition zone between 60 000 and 80 000 ft and their rate of decline with atmosphere depth is important to the design process of high-speed aircraft.

Onboard Radiation Levels

The exposures of the crew and passengers occur within a massive structure with shielding characteristics dependent on the radiation components present, the construction materials employed, and the aviation fuel present. A more complete transport code is required for the evaluation of the environment and the shielding effects of the primary structure and subsystems. Furthermore, the geometry models of the exposed individuals are required because substantial self-shielding will reduce organ exposures.

Transient Exposures

During solar particle events, the radiation levels in polar regions will increase to high exposure levels, and action must be taken to protect the crew and passengers. An atmospheric exposure model for transient solar events needs to be developed which incorporates the National Oceanographic and Atmospheric Administration (NOAA) satellite solar flare data. This exposure model will provide a real time worldwide guide for HSCT operations to minimize exposure and to provide a basis for decision making on trajectory modification.

Engineering Design Issues

A well-established fact is that the neutron component is increased by the presence of an aluminum aircraft structure and conversely attenuated in aviation fuel and in biological tissues (refs. 8, 27, 44, and 62). Using a polymer composite instead of aluminum for the primary structure could lead to reductions in the onboard exposures. Such effects are dependent on the types of particles and their energies present at the altitude of interest; improved environmental models for the physical fields are required.

In the event of large solar flare, adequate information must be displayed to the pilot for an informed decision on appropriate action. For example, decent to lower altitude requires one to know how much lower and the existence of an alternate landing site if the change in fuel consumption requires. A second alternative is to move away from the polar region to reduce exposure at cruise altitude and seek an alternative landing site if necessary. Whether such decision making is made onboard or as a part of air traffic control has important implications on the aircraft operation. In any event, an adequate onboard monitoring system is required to record the events and related exposures. If high exposures occur, reporting requirements on the exposure conditions will undoubtedly be required.

Concluding Remarks

Although the atmospheric radiation environment is better understood than when the commercial supersonic transport was first proposed in the 1960's, knowledge of the components which are biologically most important rests on theoretical predictions which have not been verified experimentally. Furthermore, there are little biological data on exposures to these components on which to base risk estimates. With the anticipated lowering of recommended exposure limits, these issues become even more important. The purpose of the present paper is to clarify current knowledge to define a means to resolve the radiation safety issues associated with future high-speed aircraft.

NASA Langley Research Center
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March 2, 1995

Appendix

High-Speed Civil Transport Aircraft Parameters

This appendix provides details relevant to an advanced high-speed passenger air transport for service in the 21st century between the United States, Europe, Asia, and the Pacific Rim (refs. 28 through 30). A fleet of 500+ aircraft with 300 passengers each is envisioned so that approximately 25 000 passengers (men, women, and children) will be at cruise altitude at any given time during any day (assuming two flights per day at 50 percent occupancy). Approximately 18 000 of those passengers are expected to be traveling the North Atlantic or North Pacific routes according to the worldwide distribution of such flights (ref. 34). Of those on board at any given time, assuming standard Western population distribution, 180 are expected to be pregnant, with 60 in the first trimester, of which 30 may be unaware of their pregnancy. A typical flight will last approximately 4 hr at altitudes between 60 000 and 80 000 ft, depending on design of the aircraft (Mach 2.4 aircraft will cruise at 65 000 ft). The HSCT crew is assumed to make 2 to 3 trips per week and accumulate flight time of 400 to 500 hr at cruise altitude per year. These factors are summarized in table A1.

Table A1. Personnel and Passenger Parameters

Altitude, ft	60 000–80 000
People aloft	25 000
People on northern routes at any given time	18 000
Pregnant	180
In first trimester	60
Crew time at altitude, hr/yr	400–500

Table A2. Aircraft Parameters

Aircraft in fleet	500
Passengers	300
Weight with zero fuel, lb	300 000
Weight of fuel, lb	500 000
Wall areal density, g/cm^2	3–4
Wall material	Polymer composite or aluminum alloy

The planned aircraft will weigh about 300 000 lb without fuel and carry up to 500 000 lb of fuel. The unfueled aircraft weight is 33 percent basic structure, 12 percent power plant, 33 percent onboard systems, and the remaining 21 percent payload. The fuel is kerosene based, and a 5-percent reserve is planned on arrival at the destination gate. The basic structural elements of the HSCT may be aluminum alloys or polymer composites. The skin areal density will be from 1.4 to 1.9 lb/ft^2 (approximately 3 to 4 g/cm^2). These parameters are summarized in table A2.

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13. ABSTRACT *(Maximum 200 words)*
High-speed commercial flight transportation is being studied for intercontinental operations in the 21st century. The projected operational characteristics for these aircraft are examined, the radiation environment as it is now known is presented, and the relevant health issues are discussed. Based on a critical examination of the data, a number of specific issues need to be addressed to ensure an adequate knowledge of the ionizing radiation health risks of these aircraft operations. Large uncertainties in our knowledge of the physical fields for high-energy neutrons and multiply-charged ion components need to be reduced. Improved methods for estimating risks in prenatal exposure need to be developed. A firm basis for solar flare monitoring and forecasting needs to be developed with means of exposure abatement.

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