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RADIATION SAFETY ISSUES IN HIGH ALTITUDE COMMERCIAL AIRCRAFT

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Abstract-The development of a global economy makes the outlook for high speed commercial intercontinental flight feasible, and the development of various configurations operating from 20 to 30 km have been proposed. In addition to the still unresolved issues relating to current commercial operations (12-16 km), the higher dose rates associated with the higher operating altitudes makes it imperative that the uncertainties in the atmospheric radiation environment and the associated health risks be re-examined. Atmospheric radiation associated with the galactic cosmic rays forms a background level which may, under some circumstances, exceed newly recommended allowable exposure limits proposed on the basis of recent evaluations of the A-bomb survivor data (due to increased risk coefficients). These larger risk coefficients, within the context of the methodology for estimating exposure limits, are resulting in exceedingly low estimated allowable exposure limits which may impact even present day flight operations and was the reason for the CEC workshop in Luxembourg (1990). At higher operating altitudes, solar particle events can produce exposures many orders of magnitude above background levels and pose significant health risks to the most sensitive individuals (such as during pregnancy). In this case the appropriate quality factors are undefined, and some evidence exists which indicates that the quality factor for stochastic effects is a substantial underestimate.

INTRODUCTION When the possibility of high-altitude supersonic commercial aviation was first seriously proposed, Foelsche brought to light a number of concerns for the associated atmospheric radiation exposure due to penetrating cosmic rays (CR) from the galaxy (GCR) and the sun (SCR) including the secondary radiations produced in collision with air nuclei. 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. *(1)*. Prior to that study, the role of atmospheric neutrons in radiation exposure was generally regarded as negligible *(2)*. The LaRC studies revealed the neutron radiation to be the major contributor to aircraft exposure which was still comfortably below allowable exposure limits except during a possible solar flare event. The main concern of these early studies was the potential prenatal injury in high altitude flight especially during a possible large solar event since crew and passengers included women of child bearing age. An advisory committee to the Federal Aviation Administration (FAA) recommended that a satellite early-warning/monitoring system be established, active onboard monitoring devices be included in the aircraft design, and that operational procedures be developed to insure that exposures on a given flight be limited to 5 mSv *(3)*. Subsequent studies by Allkofer and Heinrich showed that the penetrating GCR contribute a high LET event per gram of tissue per month which may have consequence in early prenatal exposure *(4)*.

Several factors have changed since those early studies: (A) the highly ionizing components are found to be more biologically damaging than previously assumed and the associated quality factors have been increased *(5,6)*; (B) recent epidemiological studies (especially the data on solid tumors) and more recent A-bomb survivor dosimetry have resulted in higher radiation risk coefficients for γ rays *(7,8)* resulting in lower proposed permissible limits *(5,9)*; (C) "an urgent need is recognized for better estimates of the risk of cancer from low levels of radiation" *(10)*; (D) subsequent to deregulation of the airline industry, flight crews are logging greatly increased flight hours *(11–14)*; (E) 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 *(15)*; and (F) airline crew members are now classified as radiation workers *(5,16)*. In recognition of the potential impact of these factors on present day crew exposures, the CEC organized a Workshop on Radiation Exposure of Civil Aircrew *(17)*. The workshop conclusions (mainly for subsonic exposures) are that the environment is not adequately known for reliable estimates of dose equivalent resulting mainly from uncertainty in the neutron spectra at high energies and a re-evaluation of the heavy ion component should be made. Recent studies on prenatal exposures of mice embryo at low dose of γ rays and α rays show developmental injury by α particles to have large RBE compared to quality factor and may prove of importance to estimates of risks of high energy neutron exposures characteristic of the aircraft environment *(18,19)*. Finally, it is clear that the development of advanced high-speed commercial aircraft requires some attention to the past concerns of high-speed flight but in terms of current day knowledge and uncertainty in that knowledge *(19)*.

BACKGROUND LEVELS The background levels in the atmosphere are generated by the interaction of the GCR with the interplanetary media, geomagnetic field and atmosphere resulting in modulation over the 22 year solar cycle (up to a factor of two), maximum at the magnetic poles with decline to the equator (factor of three to ten), and strong altitude dependence *(19)*. The polar regions are extensive and the northern plateau dips as far south as New York along the Atlantic coast. Indeed the most traveled international routes are along the edge of this polar region *(19)*. The uncertainty in the radiation levels in the polar region at solar minimum (where the background levels are maximum) are shown in table 1. The dose rate is measured in a tissue equivalent ion chamber and does not reflect the contributions of high LET events to the dose equivalent *(1)*. The added high LET contributions to the dose equivalent are indicated separately in the table *(19)*. The greatest contribution being the neutron component below 24 km and the penetrating heavy ions at 30 km. The main uncertainty in the neutron contribution results from the uncertainty in the neutron spectrum especially at high energy *(17,19)*.

Table I. Background Dose Equivalent Components at High Altitude and Latitude During Solar Minimum (1977)

Component	18 km	21 km	24 km	30 km
$\dot{D}, \mu Gy - hr^{-1}$	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
$\dot{H}$, μSv-hr^{-1}	14.5–30.3	16.9–35.2	18.6–38.5	24.7–36.5

SOLAR EVENTS Transient levels are generated by SCR which happen on occasion mainly during the rise or decline of the solar sunspot cycle. It was a primary objective of the LaRC measurements program to make inflight measurements during a significant solar event *(1)*. Unfortunately the largest flare of cycle 20 occurred nine months after the program was terminated. Nonetheless, an energetic (but low intensity) event occurred on 30–31 March 1969 in which measurements were made in two successive flights in the event. The inferred dose equivalent rates are shown in figure 1 along with the ground level Deep River neutron monitor count rate. Past ground level observations for intense high energy events are shown in figure 1 for which estimates of the radiation levels at 20 km are made by scaling the measured data for the 30–31 March 1969 event. Clearly large exposures can occur in flight at such high altitudes. Calculational results are in line with this simple scaling procedure *(1,19)*.

EXPOSURE ESTIMATES Nominal exposures (midrange of table 1 uncertainties) on the dominant international route (London to New York) assuming 1 000 block hours per year for the crew are shown in table 2 with other occupational exposures for comparison. Also shown in the table is the estimated exposure from the 23 Feb. 1956 solar event assuming no special attempt is made to reduce the exposure. The nominal passenger exposures for the specified flight conditions are also given. Nominal background levels at Mach 2.4 are at the limit for occupational exposure (20 mSv) and well above the recommended limits for new designs *(9)*. Actual exposures may be much higher in view of the uncertainty in table 1. If an event of the size and spectral content of the Feb. 1956 event occurs then much higher exposures may occur on a given flight. The exposure on a Mach 2.4 transport could reach 60 mSv which is well above any accepted standard for occupational exposure especially in the event of pregnancy.

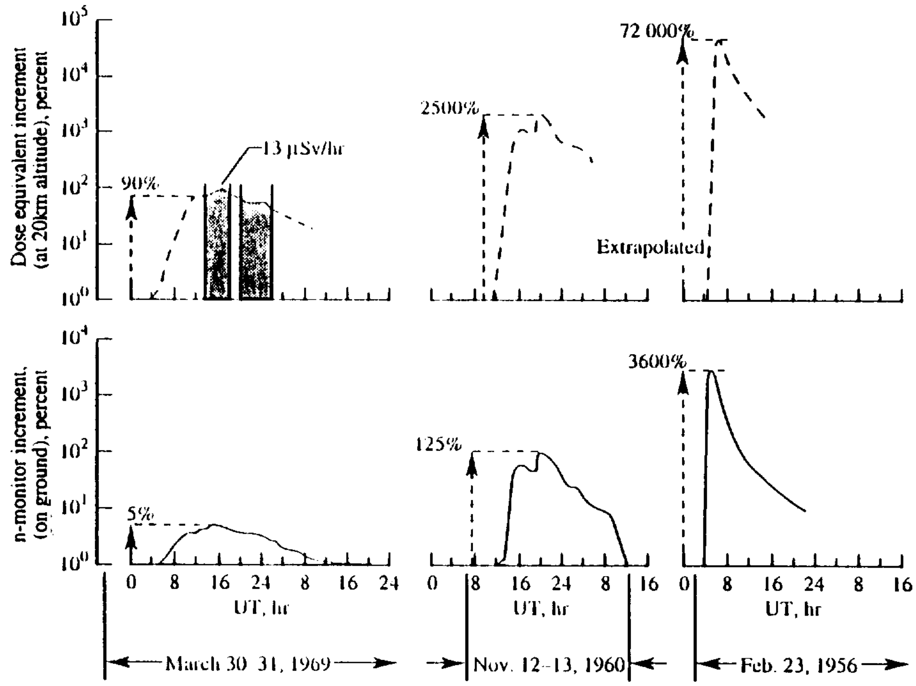

Figure 1. Energetic solar events measured on ground and at 20 km altitudes.

Most passengers in a Mach 2.4 transport make few trips each year and the exposures from background are smaller than for subsonic flights along the same route. Exposures of frequent flyers may exceed the average occupational exposure in the nuclear industry. There is planned to have a fleet of 500 or more such aircraft (perhaps more than 1000 by 2025 AD) with 150 (fifty percent occupancy) or more passengers making two trips each day so that 25,000 people will be aloft at any given time of which 180 will be pregnant. Clearly the exposure to the Feb. 1956 event would be unacceptable at Mach 2.4 and above and some means to reduce exposures is required *(3)*.

Table 2. 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 (1000 hr):		
Mach 0.85 (12 km)	≈ 14	≈ 5
Mach 2.4 (20 km)	≈ 20	≈ 60
Mach 3.2 (24 km)	~ 26	≈ 100
Mach 5.0 (30 km)	≈ 30	≈ 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.

ISSUES It is clear that the expected exposures of the passengers and crew from background levels can be high and may even be above recommended acceptable levels. Most important in this respect is that the exposure of such a large array of body tissues to high LET components is unique. Furthermore, in the event of a large solar flare the exposures could be injurious to the very young and unborn. This raises the concern that the quality factor for stochastic effects used in protection practice may not represent the RBE for developmental injury during organogenesis. Studies in prenatal mice exposures indicate that RBE for injury to developing hemopoiesis by high LET radiation's are far greater than quality factors would predict *(18)*.

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