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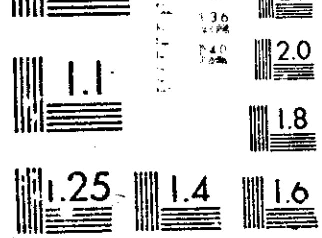

(6) COSMIC RADIATION EXPOSURE DURING AIR TRAVEL

FAA Advisory Committee on
Radiation Biology Aspects of
the Supersonic Transport

summarized and edited for the FAA by

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Abstract

In 1967 the FAA appointed an advisory committee on radiation biology aspects of SST flight. Some of the committee members were subsequently appointed to a working group to study radiation exposure during air travel in conventional jet aircraft. Presented here, in some cases in revised form, is selected material from the final reports of the full committee and the working group and related material from other sources. Included are: (i) brief descriptions of the galactic and solar cosmic radiation environment; (ii) estimates of accumulated radiation dose during air travel and associated risks of genetic and somatic effects; (iii) altitude, solar cycle, and geomagnetic latitude profiles of galactic radiation; (iv) radiation protection recommendations by the committee; (v) current status of forecasts and monitoring of solar cosmic radiation events; and (vi) operational experience related to Concorde flights.

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COSMIC RADIATION EXPOSURE DURING AIR TRAVEL

I. Introduction

More than a decade ago it was anticipated that civilian supersonic transports (SST) would be flying at altitudes in excess of 17 km. It was recognized that the possible health hazards from exposure of occupants of such airplanes to cosmic radiation needed thorough investigation. A number of national and international organizations carried out a variety of studies. The Office of Supersonic Transport Development and the Office of Aviation Medicine, both of the Federal Aviation Administration (FAA), analyzed available information on cosmic radiation and decided to institute a program of radiation measurement. In 1967 the FAA Advisory Committee on Radiation Biology Aspects of the Supersonic Transport was appointed. The main tasks of the committee were to: (i) monitor and coordinate the High Altitude Radiation Environment Stud, carried out by the FAA in cooperation with the U.S. Air Force, the Navy, and the National Aeronautics and Space Administration (NASA); (ii) promote a number of other research efforts; (iii) utilize the results of these studies, as well as data from other sources, to obtain the best information on cosmic radiation; and (iv) advise the FAA on operational and regulatory measures necessary to deal with the SST radiation problem.

Before the advisory committee ceased operating in 1974, several of its members were appointed to a working group to study radiation exposures during air travel in subsonic aircraft in the United States. Such a study was considered important because of the large number of air travelers, the long distances traveled, and the relatively high geomagnetic latitudes of most flights.

Presented here, in some cases in revised form, is selected material from reports of the advisory committee (1) and the working group (2). Some errors in the published reports have been corrected. A section entitled "Related Information Including Recent Developments" was prepared by the editors after the tenures of the advisory committee and working group had expired.

II. Radiation Environment

A. Galactic Cosmic Radiation.

The earth is continuously irradiated from all directions by nuclear particles that originate outside our solar system. This so-called primary galactic cosmic radiation impinging on the atmosphere is about 85 percent protons and 13 percent alpha particles; in the remaining 2 percent, heavier nuclei up to iron and beyond have been identified.

As the primary particles penetrate the atmosphere they undergo nuclear interactions with oxygen, nitrogen, and other atoms of the air to produce secondary particles. The secondary particles may undergo further nuclear interactions with other air atoms, and the particles thus produced are also called secondary particles. Simultaneously with the production of new particles, particles disappear from the cascade because their energy losses by air ionization leave them without sufficient energy for a nuclear interaction.

The entire atmosphere from the ground up constitutes a radiation shield with a mass-area density of 1,034 g/cm^2. After the primary cosmic ray particles have penetrated the atmosphere down to an altitude of about 24 km, about 50 percent of the original protons, 25 percent of the original alpha particles, and 3 percent or less of the original heavier nuclei still remain uncollided. At this altitude, the total dose-equivalent rate is maximum, being higher than it is at the top of the atmosphere because of the buildup of secondary particles produced in the air above 24 km. At air transport cruising altitudes, whether conventional or SST, the secondary radiation, consisting mainly of protons, neutrons, π mesons, and gamma rays, produces the major part of the dose received by occupants of an aircraft.

Because the charged cosmic ray primaries are affected by the earth's magnetic field, the cosmic radiation level in the earth's atmosphere shows a strong dependence on geomagnetic latitude. The radiation level is lowest at the geomagnetic equator where the particles tend to approach the earth at right angles to the magnetic lines of force. Here low energy particles are deflected away from the earth and only the relatively high energy particles enter the atmosphere. With increase in geomagnetic latitude, cosmic ray particles approach the earth at decreasing angles with respect to the magnetic lines of force and, consequently, lower energy particles are able to enter the atmosphere.

Superimposed on the earth's magnetic field is the interplanetary solar magnetic field which also influences the amount of galactic cosmic radiation that reaches the earth. The solar magnetic field is strongest during the maximum of the 11-year cycle of sunspot activity and weakest when sunspot activity is at its minimum.

During sunspot maximum the interplanetary solar magnetic field screens out low energy galactic primaries that would otherwise enter the earth's atmosphere at high geomagnetic latitudes. Thus the amount of variation in atmospheric galactic radiation over the 11-year sunspot cycle is latitude dependent, with the greatest variation occurring at high geomagnetic latitudes.

Altitude dependence of galactic radiation level, as indicated by air ionization, is shown in Figure 1. The measurements were made at high geomagnetic latitude during solar cycle 19 (Figure 2). In this period galactic radiation levels were lowest about 1958 (solar maximum) and highest about 1965 (solar minimum). The variation in galactic radiation level as a function of altitude and geomagnetic latitude at solar minimum is shown in Figure 3. Calculations by O'Brien and McLaughlin (5) indicate that the difference in dose-equivalent rate between solar maximum and solar minimum at 55° geomagnetic latitude increases from 9 percent at sea level to 16 percent at 18 km. At 43° geomagnetic latitude, the difference increases from 6 percent at sea level to 11 percent at 18 km.

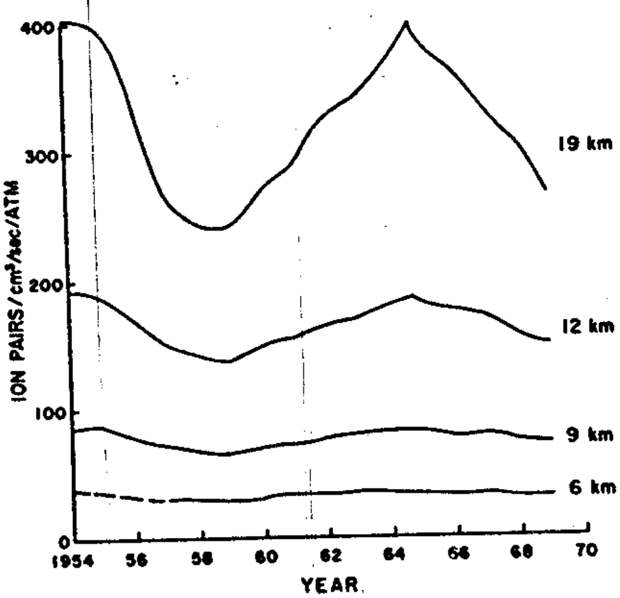

Figure 1. Galactic radiation level (indicated by air ionization) as related to phase of solar cycle and altitude at 88°N geomagnetic latitude (3). (These curves do not accurately reflect relative amounts of variation in absorbed dose rate or dose-equivalent rate.)

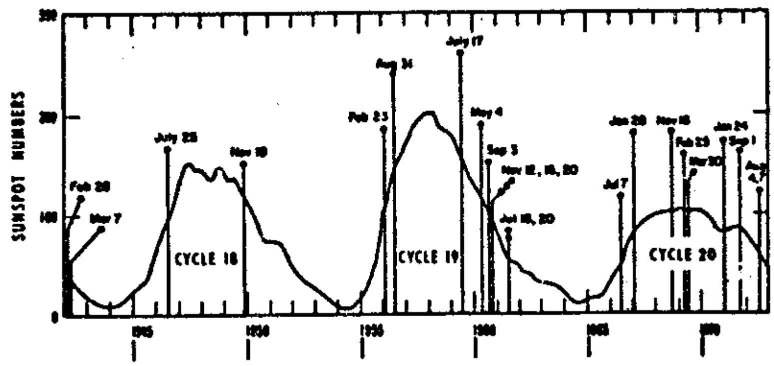

Figure 2. Recent sunspot cycles (smooth sunspot-number curve) and times of solar cosmic radiation events with proton energies of at least several hundred MeV (1).

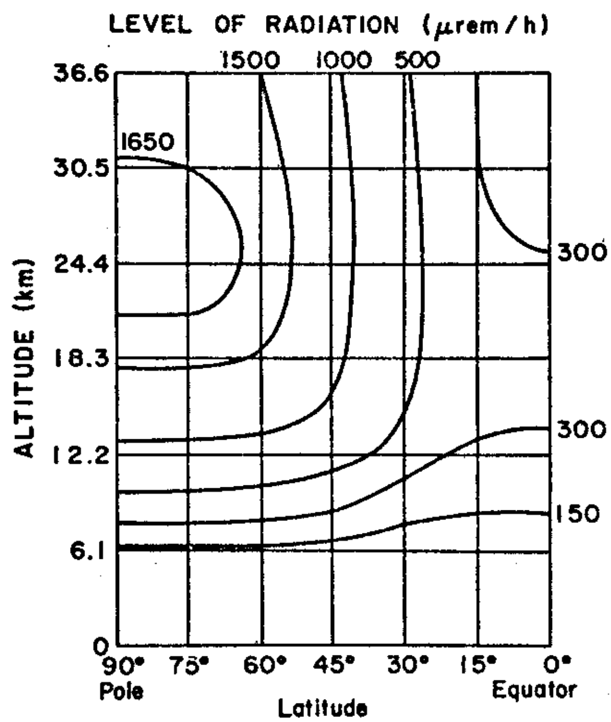

Figure 3. Galactic radiation level as a function of altitude and geomagnetic latitude, solar minimum conditions (4).

B. Solar Cosmic Radiation.

The occurrence of solar cosmic radiation events is roughly related to the 11-year sunspot cycle (Figure 2). The cosmic radiation emitted by the sun consists mainly of protons, some alpha particles, and a few heavier nuclei. The proton energies range into the GeV (10^9 electron volts) level. The energy spectrum of the solar protons is usually quite steep with relatively few high energy particles. Occasionally, however, there is an appreciable flux of protons with energies of at least several hundred MeV and the increased radiation can be detected at ground level. Figure 2 shows the time of occurrence of 23 of these so-called ground-level events during three sunspot cycles.

The following phenomena are typically associated with an intense proton-producing solar flare: Coincident with the visible flash, X-rays, ultraviolet radiation, and radio noise from the flare enter the earth's atmosphere. These electromagnetic radiation emissions continue from less than an hour up to several hours. The most energetic of the protons arrive in the atmosphere within 15 min of the onset of the visible flare. This surge of energetic protons interacting with air nuclei may produce relatively high dose-equivalent rates at SST altitude. The increases in intensity of the high energy protons and of the secondary radiation follow the same time course and reach a maximum within 4 h. In the case of the giant flare of February 23, 1956, the intensity of high energy protons peaked at 20 min and then decayed with a half-life of about 1 h. Low energy protons take longer to reach the earth than the high energy particles and continue entering the atmosphere for 1 or 2 days after the onset of the flare. Long distance radio communications are disrupted by the increased ionization of the earth's atmosphere by the X-rays, far ultraviolet radiation, and protons. There is misdirection and greater than normal absorption of radio waves in the ionosphere resulting in partial to complete signal fadeout. Radio communication problems begin with the arrival of the X-rays and ultraviolet radiation and continue until the influx of protons is abated 1 or 2 days later.

There is a great variability between individual solar cosmic ray events, with a tendency for two or three events to occur within a few days of each other.

Major solar cosmic radiation events since 1956 and estimated dose-equivalent rates are shown in Table 1. From the standpoint of a possible radiation hazard at aircraft altitudes, the February 23, 1956, and August 4, 1972, events are of particular interest. During both of these events SST passengers on a single transatlantic flight could have been exposed to more than 500 mrem, the recommended yearly limit for an individual member of the general public.

The giant solar flare of February 1956 was the largest solar proton event in at least 30 years (7). Figure 4 shows estimated maximum radiation level as a function of altitude in polar regions.

TABLE 1. Estimated Radiation Levels at Various Altitudes During Major Solar Proton Events Between 1956 and 1972 (6)

Date	Dose-Equiv. Rate at 16.2 km (mrem/h)	Altitudes (km) at High Geomagnetic Latitude at Which the Dose-Equivalent Rate Exceeded: 100 mrem/h	50 mrem/h	20 mrem/h
Feb. 23, 1956	500 +	11	9	
Jul. 16, 1959	30	20 +	18	15
Nov. 12, 1960	70	18	15	12
Nov. 15, 1960	40	20	17	14
Aug. 4, 1972	400	12	10	9

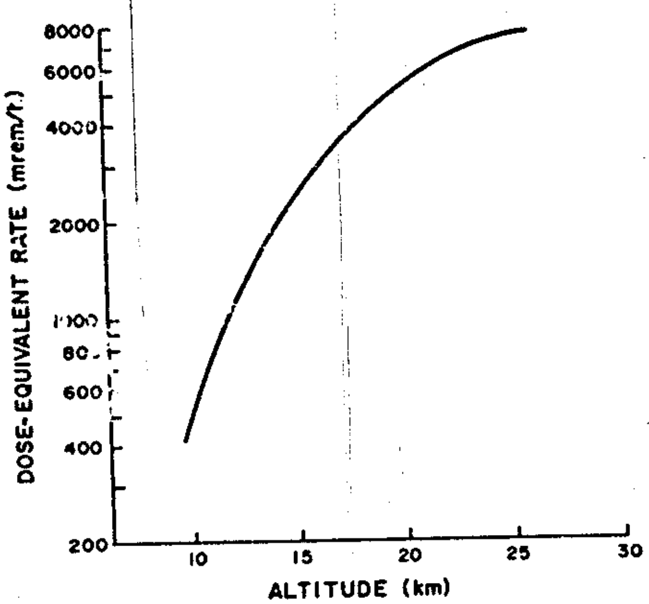

Figure 4. Upper limit estimate of dose-equivalent rate (extremity dose) versus altitude for the solar flare of February 23, 1956 (8).

III. Investigations Conducted Under Committee Auspices

A. Galactic Radiation Exposure During Air Travel in the United States and Associated Risks of Radiation Injury.

The working group appointed by the FAA Advisory Committee (section I, Introduction) investigated galactic cosmic radiation exposure during air travel in the United States (2). Radiation doses were calculated by use of a computer program (ACRE) that combined experimentally determined ion-pair and neutron-fluence data, aircraft speeds, flight profiles, and air travel statistics for 907 city-pairs.

About 25 percent of the adult population (35 million persons) flew at least once in 1973; ACRE calculations indicate they received an average dose of 2.8 mrem for the year. When averaged over the total U.S. population, the radiation dose from commercial flying was estimated to be 0.47 mrem/person per yr. According to a survey made by the Gallup organization in June, 1970, (cited by Schaefer (9)), about 0.005 percent of the adult population (7,000 persons) flew 25 or more round trips during the preceding 12-month period. Assuming each trip involved transcontinental flights, the annual radiation dose for those 7,000 frequent travelers would be 63 mrem each. For crew-members, the annual dose would be 160 mrem each. These estimated annual doses to air travelers are below the radiation guide limit of 170 mrem/yr above background recommended for the general public and well below the 500 mrem/yr maximum for an individual member of the general public.

On the basis of dose-effect relationships suggested by a committee of the National Academy of Sciences (10), the incidence of disease from radiation exposure during air travel can be estimated. From genetic effects there might result after several generations 3 to 75 additional serious disabilities per year in the total U.S. population and an increase in overall ill health of 0.0014 to 0.014 percent (this includes serious disabilities). With respect to somatic effects, namely premature deaths from cancer, the upper limit of effect is about 9 to 43 cancer deaths per year in the flying population of the United States.

These estimates of risk of radiation injury from galactic cosmic radiation should be considered preliminary only and possibly substantially in error. Some considerations that make the estimates questionable are:

(i) A convincing body of evidence indicates that at low radiation doses the relative biological effectiveness of fast neutrons may be much greater than previously assumed (11). Suggested changes in the quality factors used to convert neutron absorbed-dose rate to dose-equivalent rate would result in higher estimates of dose-equivalent rates at aircraft altitudes.

(ii) Reevaluation of data on the leukemia incidence in atomic bomb survivors of Hiroshima and Nagasaki indicates that the neutron-induced leukemias were caused by only one-fourth the neutron dose previously assumed (12). The Japanese experience is a primary source of data for estimating risk.

(iii) Neutron levels in the atmosphere are currently being reinvestigated (13,14). Initial measurements show neutron dose-equivalent rates higher than those indicated by ACRE.

(The preceding considerations indicate that the risks may be greater than estimated; the following considerations would reduce the risk estimates.)

(iv) There is some evidence that the latent period for radiation-induced cancer may be longer at low doses than at high doses (15). In some cases the latent period could exceed life expectancy.

(v) There is evidence that low doses of low-LET radiations (e.g., electrons, gamma rays) are less harmful than indicated by linear extrapolation from effects at high doses, the method used to obtain the risk estimates given here.

(vi) The present estimated risks at low dose rates are based on linear extrapolation from effects at high dose rates. No correction was made to account for risk reduction by dose protraction (16).

B. Measurements With the High Altitude Radiation Instrument System.

In 1965, the FAA entered into an agreement with the Air Force Weapons Laboratory at Kirtland Air Force Base, New Mexico, to measure the radiation at the operating altitudes of the SST (1). The High Altitude Radiation Instrument System (HARIS) developed for this study included a proportional counter operating as an LET spectrometer, an ionization chamber to measure absorbed dose, and a Geiger counter to allow comparison with previous cosmic ray balloon experiments and to give a check on change of dose rate with time (Figure 5). The HARIS was flown in Air Force planes from Eielson Air Force Base, Alaska. The primary purpose of the study was to measure solar cosmic radiation; actually most of the measurements were of galactic radiation, although the sensitivity of the HARIS was marginal for this purpose.

Data collected between October 1968 and June 1971 (at or near solar maximum), at 18.3 km and approximately 70°N geomagnetic latitude, indicated an average absorbed-dose rate from galactic radiation of 0.45 mrad/h ± 20 percent (probable error) and a dose-equivalent rate of 0.9 mrem/h ± 40 percent. The probable errors include calibration, instrument, and statistical errors.

Individual measurements over 20-min periods varied from 0.29 to 0.62 mrad/h and from 0.5 to 1.4 mrem/h. Solar proton events were measured during February, March, April, and November 1969, and January 1971, with maximum readings of 1.0 mrad/h and 2.0 mrem/h. The instrument was never aloft during a big proton event.

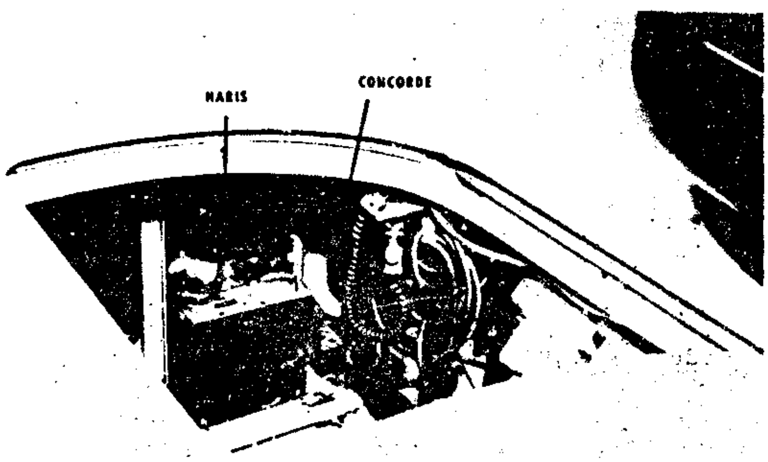

Figure 5. HARIS package and Concorde instrument in upper pressurized compartment of RB-57F. View from above the compartment.

C. Galactic Cosmic Radiation Measurements With the Brookhaven National Laboratory Dose-Equivalent Meter.

The Brookhaven National Laboratory (BNL) dose-equivalent meter was flown in U.S. Air Force planes under arrangements made by the FAA and by the Environmental Protection Agency. The instrument consists of a 20-cm-diameter tissue-equivalent chamber generating the same pulse spectrum as that obtained by a Rossi LET spectrometer. The chamber output is processed by three amplifiers with individually set values of gain and bias and digitized to provide a tape printout of absorbed dose and dose equivalent every 2 min. Radiation measurements made during 1971 and 1972, near solar maximum, are shown in Table 2.

TABLE 2. Radiation Measurements With the BNL Instrument (17,18)

Geomagnetic Latitude (°N)	Date	Altitude (km)	Absorbed-Dose Rate (mrad/h)	Dose-Equivalent Rate (mrem/h)
36.7	Aug. 29, 1972	3.0	0.018	0.025
		6.1	0.058	0.100
		9.1	0.138	0.250
		12.2	0.280	0.475
41.7	Aug. 30, 1972	3.0	0.020	0.025
		6.1	0.063	0.088
		9.1	0.150	0.245
		12.2	0.310	0.525
50.0	Jun. 17, 1972	3.0	0.022	0.035
		6.1	0.061	0.105
		9.1	0.168	0.275
		12.2	0.345	0.580
58.0	Jul. 18, 1972	3.0	0.019	0.042
		6.1	0.063	0.121
		9.1	0.170	0.290
		12.2	0.390	0.700
69.4	Jun. 29, 1971	9.1	0.159	0.234
69.6		11.6	0.288	0.489
68.4		15.2	0.489	0.793
67.3		18.3	0.603	1.039

D. Performance Tests of the Concorde Radiation Monitor.

Through the cooperation of the United Kingdom Atomic Weapons Research Establishment, a prototype of the radiation monitor used on the Concorde SST was obtained by the FAA and tested under laboratory conditions and in flight (Figure 6) (19).

The Concorde radiation monitor consists basically of three miniature Geiger counters, which measure the dose from charged-particle and gamma radiation, and a moderated boron trifluoride proportional counter, which measures the neutron dose (Figure 7). The processed signals from the two detector systems drive a single ratemeter. A four-decade logarithmic continuous indication of dose-equivalent rate is produced and displayed on a dial. A digital display of accumulated dose equivalent, in millirem, is also provided.

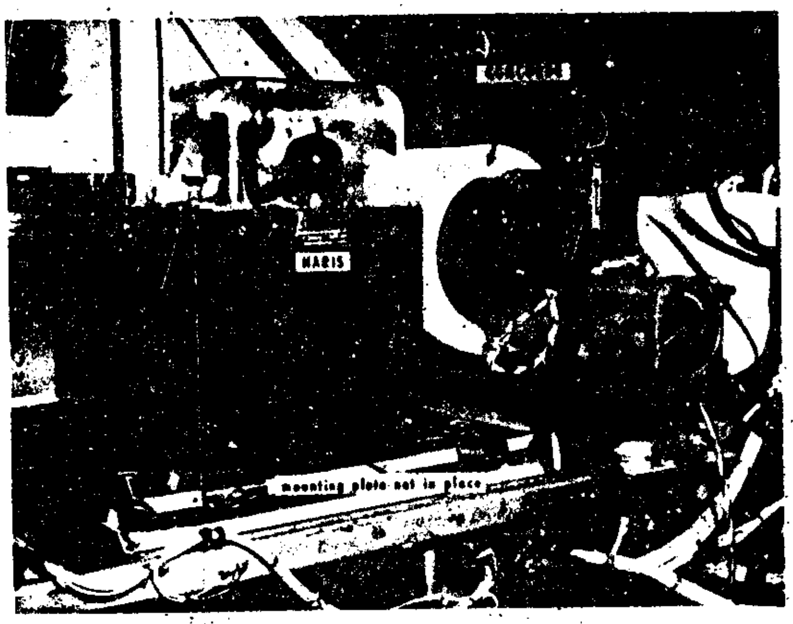

Figure 6. Concorde Instrument and HARIS package in upper pressurized compartment of kB-57F.

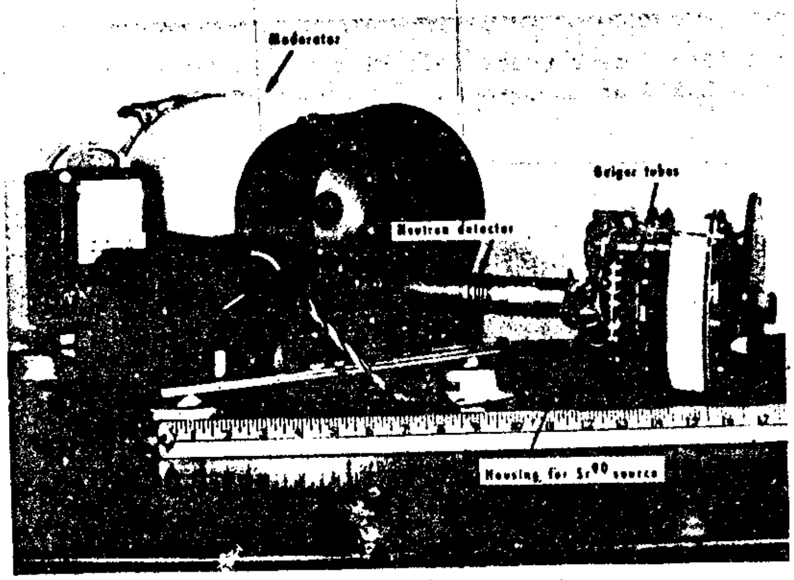

Figure 7. Concorde instrument partially disassembled.

The instrument calibration curve (log dose-rate vs. instrument reading) was reasonably linear from 0.004 to 1 rem/h for both gamma radiation and fast neutrons. Nonlinearity in the calibration curve was observed at dose rates below 0.003 rem/h. The instrument responded normally after exposure to 35 rem/h of gamma radiation. The charged particle detectors showed a directional response apparently because of the neutron moderator. The neutron detector did not show a directional response. When accumulated dose--which is shown on the digital display of the instrument--was used to compute the dose rate, the dose rate was overestimated by about 169 percent at 0.0013 rem/h and 50 percent at 0.1 rem/h.

Table 3 shows radiation measurements made with the Concorde radiation monitor aboard RB-57F aircraft flown at 18.3 km. The measurements for each flight were made at approximately the same time with both the Concorde instrument and the HARIS in the forward part of the upper pressurized compartment of an RB-57F aircraft. The Concorde instrument readings (maximum for each flight) indicated a dose rate of 0.5-0.9 mrem/h and the HARIS indicated a dose rate of 0.63-1.07 mrem/h. Thus galactic radiation measurements made with the Concorde instrument at SST altitude were reasonably consistent with those made with the HARIS. It should be recognized that both instruments were designed to measure solar cosmic radiation at levels higher than those obtained from galactic radiation.

Calibration checks in June 1969 and August 1971 indicated no change in the response of the Concorde instrument to neutrons or gamma radiation over this period of more than 2 years. These results and other tests of the Concorde instrument are described by Friedberg and Nelson (19).

TABLE 3. Radiation Measurements Made With the Concorde Instrument and the HARIS at 18.3 km and High Geomagnetic Latitude

Geomagnetic Latitude (°N)	Date	Concorde (mrem/h)	HARIS (mrem/h)
-	Nov. 3, 1969	0.9	1.07
67	Nov. 17, 1969	0.7-0.9	0.78
70	Nov. 19, 1969	0.5-0.7	0.63
70	Nov. 21, 1969	0.7-0.9	0.69
70	Nov. 21, 1969	0.7-0.9	0.65

E. Galactic Radiation Level at SST Altitude Measured With Nuclear Track Emulsion Plates.

Dr. Hermann Schaefer of the Naval Aerospace Medical Research Laboratory (NAMRL) estimated absorbed dose and dose-equivalent rates by analvses of nuclear tracks in emulsion plates located close to the HARIS (20). Flights were made in August and September 1969 (near solar maximum) at approximately 68°N geomagnetic latitude. Based on a total of 40 h of exposure at approximately 18.3 km, the dose rates were 0.58 mrad/h and 1.05 mrem/h. A sizable addition to the quoted values may be assumed to originate from local nuclear interactions of high energy primaries in tissue (so-called disintegration stars). This contribution would increase the quoted radiation levels to 0.65 mrad/h or 1.5 mrem/h.

IV. Radiation Protection Recommendations by the Committee

A. Sources of Information.

The following recommendations are based on guidelines promulgated by the National Council on Radiation Protection and Measurements (NCRP), by the International Commission on Radiological Protection, and on generally accepted practices and standards. The NCRP guidelines (21) are in substantial agreement with those of the former Federal Radiation Council. The collective constraints of these sources are sufficiently wide so that substantially different recommendations would also conform with them.

B. Maximum Permissible Dose Equivalent.

1. Crew exposure. Aircrews receive annual radiation doses that on the average are higher than those incurred in almost any other industry. Depending on scheduling, SST crewmembers could receive higher annual doses than crewmembers of subsonic aircraft. Furthermore, there is a fair possibility that SST crews may receive more than the 500-mrem/yr maximum permitted individual members of the general public.

These considerations indicate that it might be necessary to designate SST crews as occupationally exposed persons. In this case, they will have to be informed of their exposure, and they must be willing to accept whatever (presumably very small) risk it carries. The requirements of adequate radiation protection practices can be met by an appropriate monitoring system (see C below). In view of the extensive physical examinations already required, nothing more needs to be done in this area.

2. Dose limit per flight. It is recommended that the maximum dose equivalent accumulated in any one-way flight not exceed 500 mrem. This recommendation is made on the assumption that a dose of 500 mrem would occur less frequently than once per thousand one-way flights. If the 500-mrem limit is exceeded more often than expected, prompt consideration should be given to lowering the limit.

> (Editor's note: Concorde SST aircraft now operational are guided by a dose-equivalent rate limit (see page 21) rather than a total dose-equivalent in any one-way flight as recommended by the committee.)

It is assumed that pilots, in projecting the probable total dose for a flight, will take appropriate action in a conservative manner to try to keep the dose below 500 mrem. It seems impractical to set an explicit limit on the dose-equivalent rate in view of the various factors (duration of flight, traffic patterns, etc.) that must be taken into account in selecting the most advisable course of action. (See page 21 for current Concorde in-flight procedures.) The pilot will have to use personal judgment as to the kind and timing of such actions. While the harmful effects of a substantial radiation dose must be appreciated, an evasive maneuver may pose a greater hazard than that associated with exposure to a few hundred millirem. It is recommended that the FAA prepare for pilots a concise manual that provides adequate information to enable them to make any required decisions intelligently and promptly. The manual should include a discussion of possible misleading indications by onboard radiation monitoring instruments.

C. Radiation Warning.

1. Basic considerations. During the past few decades when reasonably accurate assessments of solar flare radiation have been made, the dose-equivalent rates have rarely indicated a significant hazard to persons spending a few hours at SST altitudes. Nevertheless, it is considered essential that reliable radiation warning systems be instituted for the following reasons: (i) In at least two recorded instances occupants of an SST on a routine flight very likely would have received a dose exceeding 500 mrem. (ii) The possibility of solar proton events considerably larger than any previously recorded cannot be excluded. (iii) It may well develop that the limit of 500 mrem/flight will be challenged, or that claims will be made that the dose in specific flights exceeded 500 mrem. Under these conditions knowledge of the actual doses would be essential, and failure to obtain this information could be considered negligence.

2. Onboard radiation monitor. Each SST aircraft should be equipped with airborne radiation detection devices to indicate readily to the flight crew the dose-equivalent rate of cosmic radiation and the cumulative dose throughout each flight.

At least two instruments are required so that malfunction of either instrument can be recognized by different responses. The instruments should have a warning light and buzzer that operate when the dose-equivalent rate exceeds 100 mrem/h. The instruments should indicate dose-equivalent rate up to 10,000 mrem/h to an accuracy of $\pm$ (30 percent + 1 mrem/h). After completion of each flight, the accumulated dose and any improper instrument performance should be recorded. A malfunctioning instrument should be repaired or replaced before the next flight, and thorough calibration should be performed at least once a year.

3. Satellite warning systems. It is recommended that a system be developed in which measurements by satellite-based radiation monitors are used as input to a computer programed to yield dose-equivalent rate as a function of altitude and geographic location. To adequately cover the energy range of biological interest, the radiation instruments should be able to measure particle energies up to 1 GeV. Communication links that are reliable during solar cosmic radiation events are needed to transmit the radiation data from the computer to air traffic control centers and aircraft in flight. One obvious advantage of such a system is that aircraft on the ground could be warned before takeoff if the radiation level exceeded the acceptable limit. The satellite warning system should not be relied on exclusively, however; each SST should have onboard monitoring equipment.

V. Related Information Including Recent Developments

A. Altitude Profiles of Galactic Radiation: Comparison of Data From Different Sources.

Figures 8, 9, and 10 show altitude profiles of galactic radiation according to results of ACRE (section III A), BNL (section III C), the Health and Safety Laboratory (HASL) (5), and Langley Research Center (LRC) (22). ACRE profiles of galactic radiation are of special interest because computer program ACRE was used to generate the radiation doses from which risks of radiation injury to air travelers were estimated.

The figures show that at altitudes above 9.3 km ACRE-generated dose-equivalent rates are lower than the other estimates; the differences increase with altitudes up to at least 18 km. Below 9.3 km, estimates based on ACRE curves are higher than the others. The shoulder in the ACRE curves below 9.3 km resulted from the linear interpolation between radiation measurements at 9.3 km and ground level. The ACRE curves would be closer to the HASL and BNL curves at low altitudes if all the available low altitude data had been included in the ACRE program.

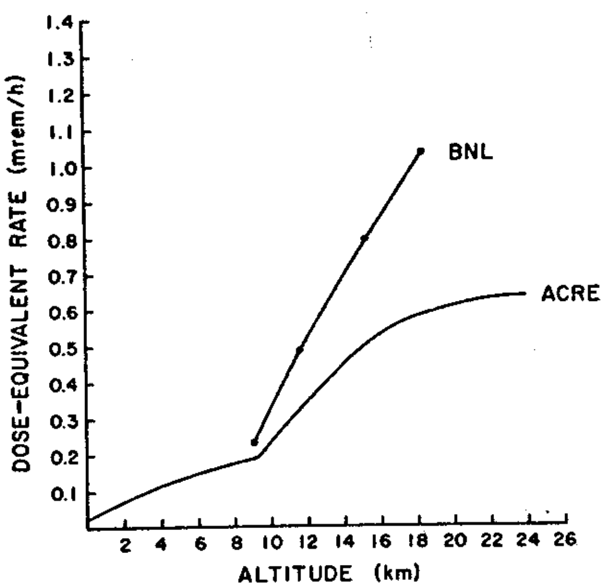

Figure 8. Galactic radiation level as a function of altitude, at or near solar maximum: ACRE at 69°N geomagnetic latitude, BNL at 67°-70°N.

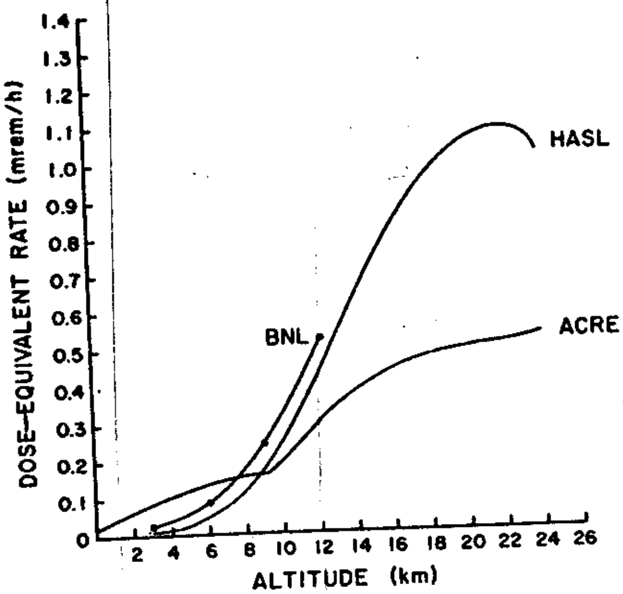

Figure 9. Galactic radiation level as a function of altitude, at or near solar maximum: ACRE and HASL at 43°N geomagnetic latitude, BNL at 42°N.

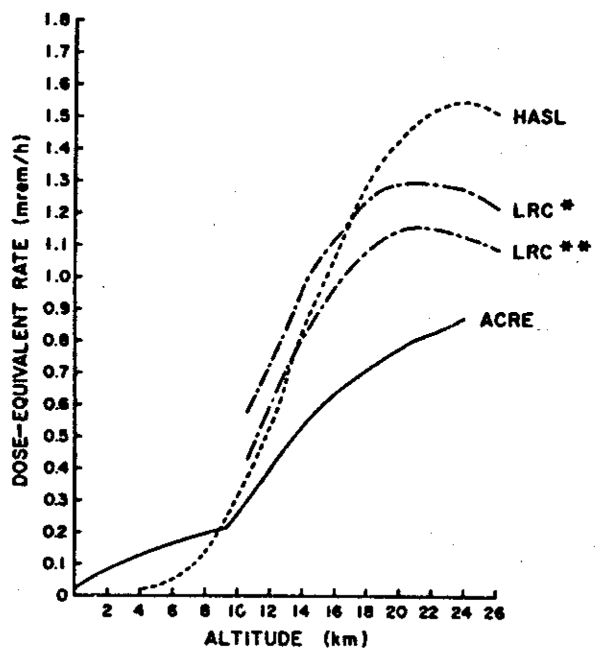

Figure 10. Galactic radiation level as a function of altitude, solar average conditions: ACRE and HASL at 55°N geomagnetic latitude, LRC at "high geomagnetic latitudes." *Extremities, **Center of Body.

In Table 4 the ACRE and other estimates are compared at 11.0 and 18.3 km. At 11.0 km the other estimates ranged from 24 to 88 percent higher than ACRE, and at 18.3 km, 38 to 159 percent higher. At subsonic cruise altitudes, radiation dose estimates by ACRE and HASL agree reasonably well. Thus on a simulated flight from New York to Los Angeles, at a cruise altitude of 11.0 km, ACRE indicated an accumulated dose of 1.27 mrem from galactic radiation (solar average conditions) (2); a similar calculation based on HASL data yielded 1.59 mrem, 25 percent higher.

TABLE 4. ACRE Results Compared With Other Estimates of Galactic Radiation Dose-Equivalent Rate[1]

Source of Data	Altitude 11.0 km	Altitude 18.3 km
	At or near 55°N, solar average[2]	
ACRE	0.33	0.73
HASL	0.41 (+24%)	1.32 (+81%)
LRC		
Center of body	0.49 (+48%)	1.10 (+51%)
Extremities	0.62 (+88%)	1.25 (+71%)
	42°, 43°N, at or near solar maximum[3]	
ACRE	0.24	0.47
HASL	0.33 (+37%)	0.98 (+109%)
BNL	0.39 (+63%)	---
	67°-70°N, at or near solar maximum[4]	
ACRE	0.29	0.58
BNL	0.41 (+41%)	1.04 (+79%)
Concorde	---	0.80 (+38%)
HARIS	---	0.90 (+55%)
NAMRL	---	1.50 (+159%)

[1]Results given in mrem/h with percentage difference from ACRE shown in parentheses.

[2]From Figure 10.

[3]From Figure 9.

[4]ACRE and BNL from Figure 8; Concorde from section III D; HARIS from III B; and NAMRL from III E.

B. Forecasts and Monitoring of Solar Cosmic Radiation Events.[1]

The Space Environmental Services Center (SESC) of the National Oceanic and Atmospheric Administration in Boulder, Colorado, collects and disseminates information on solar activity and associated disturbances in the earth's atmosphere and in outer space. Since 1969, SESC has provided forecasts of the radiation level at an altitude of 19.8 km over the polar cap (no geomagnetic shielding) in support of the Concorde SST program (23). These forecasts are issued daily and give existing conditions and predictions for the following 3 days. The radiation conditions are reported in terms of a color code: green, < 10 mrem/h; amber, 10-100 mrem/h; and red, > 100 mrem/h. A 1977 review by Sauer and Stonehocker (23) indicates that reliable forecasting of major solar cosmic radiation events had not yet been achieved. Data cited in the report are from March 22, 1971, through August 1972. During this period, 12 days were forecast to have a "significant" probability of condition red. Subsequently, it was concluded on the basis of satellite measurements that the only condition red day during this period was August 4, when the dose-equivalent rate at 19.8 km was estimated to be 351 mrem/h; however, August 4 was not one of the 12 days forecast to be condition red. According to a recent (1979) personal communication from Gary Heckman of SESC, the situation has not improved for forecasts made a day or more in advance.

SESC receives charged particle data continuously in real time from sensors on board the geostationary satellites GOES-2 and GOES-3. The sensors monitor proton flux from 0.8 to 500 MeV in seven energy ranges and alpha flux from 4 to 392 MeV in six energy ranges. The satellite telemetry is received near Boulder and transmitted by telephone line to SESC for processing. From the particle data, a transport code derived by Flamm and Lingenfelter (24) is used to estimate the radiation level at 19.8 km over the polar cap. Estimated dose rates are based on the satellite measurements of primary protons and calculated secondary neutrons and protons. The calculations are made in real time, continuously. A GOES-D satellite, scheduled to be launched in the mid-1980's, will have instruments to measure proton and alpha particle shape up to 850 MeV and integral flux above 850 MeV. The data will be transmitted to SESC continuously in real time. Prototype radiation sensors are now being tested aboard the satellite TIROS-N (25).

Dose-equivalent rate estimates based on the Flamm and Lingenfelter transport code may be in error by a factor of 2 or 3. More recent data on the transport of protons through the atmosphere have not been incorporated into the calculations. Also, the contribution of alpha particles to the radiation level is not taken into account. Studies on alpha particle transport are being undertaken at the Lawrence Berkeley Laboratory.

Radio communication systems that could be used to transmit radiation data to individual aircraft are described by Sauer and Stonehocker (23).

[1]The editors thank Gary R. Heckman, National Oceanic and Atmospheric Administration, and John W. Wilson, NASA Langley Research Center, for their assistance in the preparation of part B.

C. Operational Experience Related to Concorde Flights.

All Concordes (British and French) are equipped with a radiation monitor that measures dose-equivalent rate and accumulated dose equivalent (see section III D). In-flight procedures during a solar cosmic radiation event conform to recommendations of the International Civil Aviation Organization Technical Panel on Supersonic Transport Operations (26). If the radiation level in the aircraft reaches 10 mrem/h (alert level) Air Traffic Control must be notified that the aircraft may have to be flown at a lower altitude. If the radiation level reaches 50 mrem/h (action level) the pilot must request clearance to fly at a lower altitude.

Radiation measurements made during commercial flights of Air France Concordes in 1976 and 1977 are now available (27). Neither the action level nor the alert level was reached on any Air France flight during that time period. The highest average dose-equivalent rate on a single flight was between 6 and 7 mrem/h (Table 5). On more than 99 percent of the flights, the average radiation level was less than 4 mrem/h. On the North Atlantic route between Paris and the United States the average radiation level was 1.52 mrem/h, which is 79 percent higher than the average of 0.85 mrem/h for other routes (Table 6). The other routes were mostly between Paris and South America. That the higher readings were obtained on the higher latitude route is consistent with the known relationship between galactic cosmic radiation level and geomagnetic latitude (see section II A and Figure 3).

At 1.52 mrem/h (North Atlantic route), the maximum permissible radiation dose per year (500 mrem) for individual members of the general public (see section IV) would be reached in (500/1.52=) 329 h. This flying time is equivalent to 84 flights between Paris and the United States (42 round trips). The annual limit for persons classified as radiation workers, 5,000 mrem would be reached in (5,000/1.52=) 3,289 h or 842 flights on this route. For flights at lower geomagnetic latitudes it would take longer to reach either of the two radiation limits.

TABLE 5. Distribution of Air France Concorde Flights During 1976 and 1977 as a Function of Radiation Level

Average Dose-Equivalent Rate (mrem/h)	North Atlantic Route[1]		Other Routes[2]		All Routes	
	1976	1977	1976	1977	1976-77	Cumulative %[3]
<1	12	30	418	429	889	45.5
1-2	161	457	139	176	933	93.3
2-3	14	49	12	20	95	98.2
3-4	5	5	7	10	27	99.6
4-5	0	1	3	3	7	99.9
5-6	0	0	0	0	0	99.9
6-7	0	0	1	1	2	100.0
Total	192	542	580	639	1,953	

[1]Paris-New York and Washington.

[2]Almost entirely Paris-Rio de Janeiro and Caracas.

[3]Percentage of flights at indicated radiation level or lower.

TABLE 6. Cosmic Radiation Levels in Air France Concordes

Year	Number of Flights	Hours in Flight	Average Dose-Equivalent Rate (mrem/h)
		North Atlantic Route[1]	
1976	192	758	1.49
1977	542	2,114.5	1.53
1976-77	734	2,872.5	1.52
		Other Routes[2]	
1976	580	1,884	0.78
1977	639	1,862.5	0.93
1976-77	1,219	3,746.5	0.85
		All Routes	
1976	772	2,642	0.99
1977	1,181	3,977	1.25
1976-77	1,953	6,619	1.14

[1]Paris-New York and Washington

[2]Almost entirely Paris-Rio de Janeiro and Caracas.

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