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RADIOLOGICAL HAZARDS TO AIR COMMERCE

by **W. S. Smith**



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Federal Aviation Administration
Office of Environmental Quality
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16. Abstract A survey of existing literature concerning radiological hazards to air commerce has been completed. A preliminary assessment of three major sources of potentially significant ionizing radiation has indicated that although some data are lacking, no actual danger to either passengers or crew has been documented. Cosmic radiation from galactic sources represents a relatively well understood and easily predictable phenomenon. Solar flare activity and nuclear testing episodes, however, are infrequent events which require an ongoing effort to maintain a current understanding of health and safety related issues.					
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PREFACE

This document was prepared for the Federal Aviation Administration Office of Environmental Quality as an internal staff review of potential radiological hazards associated with air commerce. The author is indebted to his many colleagues who generously provided their special expertise in various aspects of this assessment.

TABLE OF CONTENTS

	Page
1. Introduction	1
2. Radiation Protection	1
3. Galactic Cosmic Radiation	10
4. Solar Flare Events	14
5. Debris From Nuclear Testing	20
6. Miscellaneous	28
7. Conclusions	32
8. References	35

LIST OF FIGURES

Figure 1: Dose Equivalent Index Rate	11
Figure 2: Annual Mean Sunspot Number R for the Years 1700 to 1973	15
Figure 3: Recent Sunspot Cycles (Smooth Sunspot Number Curve) and Solar Proton Events with $E_{\max} \geq 400$ MeV Measured at Ground Level	16
Figure 4: Mean Debris Top and Base as a Function of Total Weapon Yield for an Air Burst	22

LIST OF TABLES

Table 1: Summary of Effects Resulting from Whole Body Exposure to Radiation to Man	5
Table 2: Maximum Permissible Dose Equivalents	6

TABLE OF CONTENTS (Continued)

Table 3:	Surface Contamination Guides for Release to Non-Controlled Areas	8
Table 4:	IATA Recommended Limits for Airframe Contamination	9
Table 5:	Solar Proton Events Resulting in Radiation Dose Equivalent Index Rates in Excess of 10 mrem hr ⁻¹	17
Table 6:	Estimated Dose Equivalent Index Rates at Various Altitudes for Major Solar Proton Events 1956 to 1972	18
Table 7:	Comparison of Typical Radiation Levels	33
Table 8:	Comparison of Common Risks	35

Definitions and Terms

Throughout this report, standard units and definitions will be adhered to, which are briefly described as follows:

rem (roentgen equivalent man) - unit of biological dose equivalent; 1 millirem (mrem) roughly equals the energy, in ergs, deposited in ten grams of material.

gamma (γ) - a quantum unit of electromagnetic radiation; a high energy photon capable of deep penetration in organic or inorganic materials.

beta (β) - electron or positron emitted during radioactive decay; limited penetrating power.

free radical - a highly reactive organic or inorganic molecular fragment in which at least one electron is unpaired and is free to interact with the surrounding medium.

1. INTRODUCTION

Early feasibility studies of the previous decade addressing various aspects of supersonic flight compelled the Federal Aviation Administration (FAA) to develop a better understanding of the potential extent and effects of increased exposure to natural ionizing radiation. Concurrently, much valuable data were also gathered pertaining to radiation effects at subsonic aircraft cruise altitudes. More recently, attention has been focussed on sources of man-made atmospheric radioactivity. Despite the Nuclear Test Ban Treaty, the activity by nonsignatory nations has demonstrated the necessity for adopting special precautionary measures which might be needed to avoid airspace contaminated by nuclear debris.

This report summarizes the data and experience gained thusfar by the Office of Environmental Quality with regard to three potential radiological hazards to air commerce; galactic cosmic radiation, solar flare events, and nuclear test debris. In order to assess the significance of the health and safety risks involved, and place these data in perspective, comparisons are made with other man-made and natural radiation contributions as well as risks inherent in common day-to-day experiences.

2. RADIATION PROTECTION

It is worthwhile to preface any discussion of potential health hazards and their avoidance with a review of existing maximum permissible exposure levels, as

established by the National Council for Radiation Protection (NCRP), and the evidential rationale upon which these standards are based¹. Other advisory groups such as the International Commission on Radiological Protection, United Nations Scientific Committee on the Effects of Atomic Radiation, etc. have recommended numerically similar limits in all applicable situations.

Generally two types of biological radiation damage may be defined. High-energy ionizing radiation which impinges on cellular material directly induces free-radical formation from essential biochemical molecules and also creates radiolysis products of water (such as hydrogen peroxide, a highly oxidizing molecule) which interact with other tissue substances and interferes with the normal production of ATP². Genetic damage results when a germ cell, either egg or sperm, undergoes an internal change as a result of the transition of some ionizing radiation. Somatic damage results when somatic cells, those which do not participate in species continuation (such as white blood cells), dysfunction due to radiation effects.

The consequences of genetic damage are manifested in future generations when the altered germ cell unites to form a new organism. These consequences may not become apparent for many generations. Genetic effects are more properly considered in the context of a uniform dose to the general population, rather than considering one individual, since the probability of genetic damage per individual is extremely small³. In this connection the main consideration in the control of genetic damage is the burden to society in future generations

imposed by an increase in the proportion of living individuals with deleterious mutations. No evidence, either in a controlled laboratory situation or by empirical observation, is available for the genetic dose-effect relationship in humans⁴. All relevant studies to date have utilized laboratory mice. Typically, laboratory tests such as these, involve a great deal of uncertainty. This is because of the necessity for the extrapolation of effects at high doses to those of low doses in order to accumulate a statistically significant number of ascribable results. The alternative experiment, applying low doses encountered in realistic situations to a large number of mice, is prohibitive. (For example, in order to demonstrate an increase of 0.5% in the mutation rate caused by an increase of 170 mrem/year, a population of 8 billion mice would need to be studied for 20 years⁴.) This extrapolation procedure is believed by most researchers to severely overestimate the effects of low doses. This overestimate may be regarded as desirable, in that a wide margin of safety is implicit in recommended dose restrictions. It is important, however, to maintain an awareness that recommended exposures may be substantially conservative upper limits of risk rather than threshold limits which, if exceeded, are estimated to likely cause damage.

Somatic cell damage may be manifested in neoplastic diseases such as leukemia, eye cataracts, growth and development retardation, and shortening of life span. Extreme overexposures result in symptoms of "radiation sickness." Some empirical data in fact exists for estimating human effects of somatic radiation

damage. Data at extremely high dose rates exists for the survivors of the Hiroshima and Nagasaki atomic bomb blasts and from patients undergoing radiation therapy. Table 1 contains a summary of health effects for such acute radiation doses. Applying a linear regression to this data, radiobiologists estimate that the somatic effect response results in one or two cases of leukemia per million people per 1,000 mrem total population dose per year⁵. The linearity of the effect at low dose rates has been widely questioned, however, since clear-cut increases in deaths are only detectable for population groups receiving more than 300,000 mrem. The philosophical-regulatory dicotomy was expressed, in a special position paper issued by NCRP, as follows⁶:

"The NCRP wishes to caution governmental policy-making agencies of the unreasonableness of interpreting or assuming 'upper limit' estimates of carcinogenic risks at low radiation levels, derived by linear extrapolation from data at high doses and dose rates, as actual risks, and of basing unduly restrictive policies on such an interpretation or assumption. . . . Undue concern, as well as carelessness with regard to radiation hazards, is considered detrimental to the public interest."

NCRP dose limits as listed in Table 2 pertain to three categories of protective action. Although some rationale may exist for the consideration of aircraft crews as occupationally exposed, present data suggests that both crew and passenger doses are well below the limits set for occasionally exposed indivi-

TABLE 1

SUMMARY OF EFFECTS TO PEOPLE RESULTING FROM WHOLE BODY RADIATION EXPOSURE

	<u>Mild Dose</u>		<u>Moderate Dose</u>		<u>Median Lethal Dose</u>	<u>Lethal Dose</u>
	<u>0-25 r</u>	<u>50 r</u>	<u>100 r</u>	<u>200 r</u>	<u>400 r</u>	<u>600 r</u>
No detectable clinical effects		Slight transient reductions in Lymphocytes and Neutrophils	Nausea and fatigue, with possible vomiting above 125 r	Nausea and vomiting within 24 hours	Nausea and vomiting in 1 to 2 hours	Nausea and vomiting in 1 to 2 hours
Probably no delayed effects		No other clinically detectable effects.	Reduction in Lymphocytes and neutrophils with delayed recovery.	Latent period of about one week; perhaps longer.	Latent period, perhaps as long as one week.	Short latent period following initial nausea.
5		Delayed effects possible, but serious effect on average individual very improbable.	Delayed effects may shorten life expectancy as much as one per cent.	Following latent period, epilation, loss of appetite, and general malaise.	Beginning epilation, loss of appetite, and general malaise accompanied by fever and severe inflammation of mouth and throat the third week.	Diarrhoea, vomiting, inflammation of mouth and throat toward end of first week.
				Sore throat, pallor, petechiae, diarrhoea.	Pallor, petechiae, diarrhoea, nosebleeds, rapid emaciation about the fourth week.	Fever, rapid "emaciation" and death as early as the second week with a possible eventual death to 100% of exposed individuals.
				Moderate emaciation		
				Possible death in 2 to 6 weeks in a small portion of individuals.	Some deaths in 2 to 6 weeks. Possible eventual death to 50% of the exposed individuals.	
				Recovery likely unless complicated by poor previous health, superimposed injuries or infections.		

*“The Effects of Atomic Weapons,” U.S. Government Printing Office, 1950

TABLE 2
MAXIMUM PERMISSIBLE DOSE EQUIVALENTS^a

<u>Occupational Exposure</u>	
Prospective annual limit	5,000 mrems in any one year
Long-term accumulation	(N-18) x 5000 mrems where N is age in years
Fertile women	500 mrems in gestation period
<u>Public or Occasionally Exposed Individuals</u>	
Individual or Occasional	500 mrems in any one year
Students	100 mrems in any one year
<u>Population Dose Limits</u>	
Genetic	170 mrem average per year
Somatic	170 mrem average per year

^aReference 1

dual members of the public. The fundamental number below which an acceptable risk is deemed to exist (no biological effects can be detected) is 5,000 mrem/year*, that recommended for radiation workers⁷. To be consistent with ex-

* Two recently publicized studies of the effects of low-level radiation on workers at the Hanford, Washington Nuclear Facility and the Portsmouth Naval Shipyard, New Hampshire have indicated that the accepted dose limit for occupationally exposed individuals should be reconsidered. Although a lowering of this value by as much as a factor of ten has been suggested by some scientists, the limited statistical data base has prevented universal acceptance of this proposal. Thus, although some revision in this dose limit may eventually be considered, recommendations discussed herein are currently accepted.

isting studies, the limit for any individual within the public was set at 500 mrem/year, since minors are about ten times more susceptible than older persons and cannot be separated from the population in practice⁸. For total population doses it is assumed that the majority of individuals do not vary from the average by more than a factor of three, therefore a further reduction by this factor was recommended⁸.

A problem of particular interest to aircraft operations arises with regard to radioactive material which is temporarily fixed to a surface rather than distributed uniformly in the environment. The dose received by man is highly dependent upon the nature of the contact made, the average distance from the source, the energy of the radiation, and the extent to which the contamination may be removed and metabolized. Standards for the permissible amounts of surface contamination have not been established by any governmental authority in the United States⁹. The philosophy developed by NCRP requires an institutional effort to confine surface activity to levels "as low as is practicable." This implies that limits be set on the basis of not only health considerations but also that obtainable without undue economic hardship¹⁰. Surface contamination limits adopted by U. S. nuclear institutions and industrial organizations, therefore, exhibit extreme variability. On the other hand, most foreign organizations have used essentially the same criteria originated by Dunster and Barnes⁹. A comparison of these limits is shown in Table 3.

TABLE 3

SURFACE CONTAMINATION GUIDES FOR RELEASE TO NON-CONTROLLED AREAS^a

<u>Type of Facility or Reference</u>	<u>ACTIVITY</u>	
	<u>Total (fixed + removable)</u>	<u>Removable</u>
Saenger	.06 mrem/hr	undetectable
LASL-1835	.05 mrem/hr	undetectable
General Dynamics	.1 mrem/hr	undetectable
Barnes	660 dpm/cm ² ^b	—
Dunster	—	220 dpm/cm ²
UK Ministry of Health	—	220 dpm/cm ²
Major U.S. Nuclear Centers	.06-2.0 mrem/hr	undetectable to .8 dpm/cm ²
Recommendations of Other Countries	110-220 dpm/cm ²	—

^aReference 9^bdpm — nuclear disintegrations per minute. The mrem/hr equivalent depends somewhat on the identity of the decaying isotope(s).

In adopting limits for FAA use in defining various operational decision levels, consideration was given to both the infrequency of probable contact and the most common work situations in which contact would be made. In this connection severe economic hardship could be inflicted only during an extremely limited period of time. The "as low as is practicable" concept exercised

over systematic long term exposures, therefore, loses applicability. Current FAA practice, which has been coordinated with the U. S. Environmental Protection Agency (EPA), regarding surface contamination levels for aircraft exteriors is consistent with limits given by Dunster and Barnes and those recommended by the International Air Transport Association (IATA) to its member airlines¹¹. IATA decision levels are shown in Table 4.

TABLE 4

IATA RECOMMENDED LIMITS FOR AIRFRAME CONTAMINATION^a

<u>Dose Rate dpm/cm²</u>	<u>Action</u>
<2	No Action
2-22	Survey as a Precaution
22-220	Survey and Swipe Test; Health Precautions and Routine Cleaning
>220	Detailed Survey, Swipe Tests; Confinement, Decontamination; Strict Health Precautions and Professional Supervision

^aReference 11

3. GALACTIC COSMIC RADIATION

Natural radiation sources at subsonic and supersonic flight altitudes are primarily due to galactic cosmic radiation and infrequent bombardments of solar cosmic radiation. Galactic radiation is composed of high energy particles (i. e. , 85% protons, 13% alpha particles) accelerated to relativistic speeds by forces originating in deep space¹². Their exact source and acceleration mechanism are currently a matter of ongoing scientific research¹³.

Geomagnetic field lines which encompass the earth from pole to pole in a doughnut-like pattern strongly influence the radiation level at specific geographic locations. Because of the magnetic deflection of charged particles, the flux of cosmic radiation is highest in the polar regions where particles traveling nearly parallel to the lines of force are minimally deflected. Conversely, the radiation level is lowest towards equatorial regions where perpendicular lines of force induce maximum deflection.

In addition to the earth's magnetic field, primary cosmic ray intensity is also regulated by the interplanetary solar magnetic dipole field¹⁴. The solar magnetic field is strongest during the maximum in the 11-year solar sunspot cycle and weakest during the period of minimum solar activity. Thus an 11-year modulation effect is observed in which cosmic radiation levels are inversely related to solar activity.

As the primary particles penetrate the upper atmosphere, their energy is dissipated by collisions and inelastic interactions with other atmospheric consti-

tments. The major inelastic process of importance to radiological dose considerations is the production of secondary particles such as neutrons⁵.

At an altitude of approximately 20 km the total dose rate is maximized due to the buildup of secondary nucleons. Thus, the major part of the dose received by occupants of subsonic or supersonic aircraft is the indirect component of cosmic radiation. The net result of these three effects is shown in Figure 1.

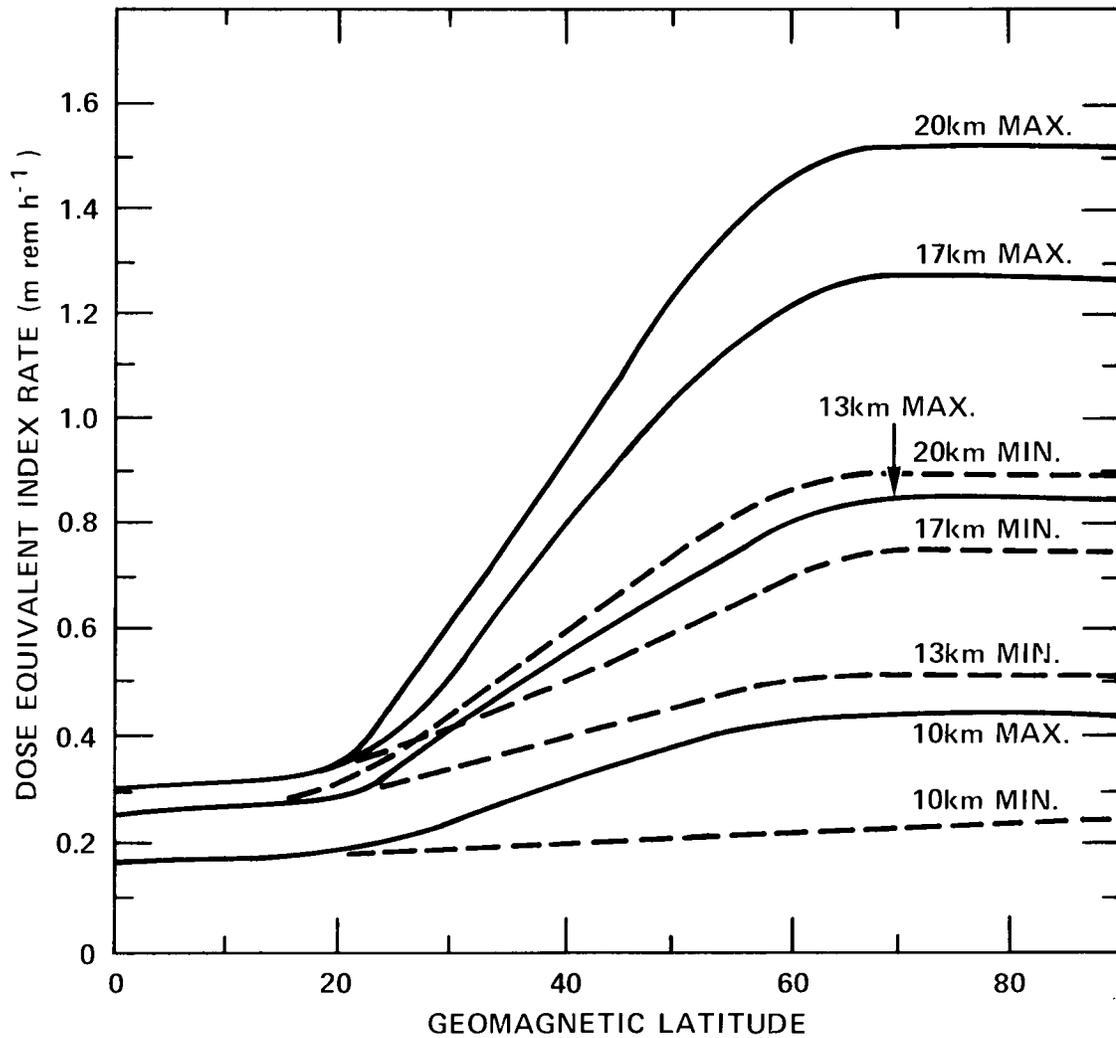


FIGURE 1. DOSE EQUIVALENT INDEX RATE. MAXIMUM (SOLID LINES) AND MINIMUM (BROKEN LINES) DURING SOLAR CYCLE AS A FUNCTION OF GEOMAGNETIC LATITUDE AND ALTITUDE. (REFERENCE 15)

In 1967 a detailed study of the effects of cosmic radiation exposure in supersonic and subsonic flight was undertaken by the Advisory Committee for Radiation Biology Aspects of the SST (ACRB). This Federal Aviation Administration-appointed interdisciplinary body of scientists attempted to analyze all available information pertaining to cosmic radiation and initiated a program of radiation measurement aboard selected aircraft. The ultimate goal of the Committee was the quantification of expected doses for passengers and crew, the issuance of recommendations concerning maximum permissible doses for passengers and crew, and an estimate of the necessity for and feasibility of radiation protective measures. Despite the termination of the U. S. SST program in 1971, the FAA continued the operation of this Committee until 1974 in order to benefit from reports of its work. Various follow-up studies by some Committee members are still in progress. Interim reports were issued throughout the operational period of the study and are condensed in the Final Report published in the open literature in 1975¹⁵.

With specific regard to the doses expected from cosmic radiation, the Committee addressed two questions within the context of NCRP dose recommendations:

What is the expected dose to any individual or occasional occupant of a subsonic or supersonic aircraft? What is the average dose to the U. S. population and hence the contribution to the genetic pool? To summarize the expressed and implied conclusions of the Committee:

- The data collected and analyzed which resulted in Figure 1 implies that occupants of supersonic aircraft receive a higher dose rate than occupants of subsonic aircraft flying at identical latitudes.
- The total dose received per flight, however, can be equal or greater for subsonic flights than SST flights, owing to the longer time spent traveling between identical city-pairs.
- Assuming that a typical crew spends about 40 hr/month at flight (i. e. , cruising) altitude, and using the Committee data in Figure 1, one may estimate that the supersonic aircraft crew may receive in excess of 500 mrem/year, while a subsonic aircraft crew receives less than 200 mrem/year for high latitude flights.
- In this connection, supersonic crews might be designated as "occupationally exposed" with some justification; however, the dose typically received by them is still substantially below the recommended limit of 5,000 mrem/year for occupational exposure, and is not subject to significant uncontrollable variation resulting from human error.
- The exposure of passengers will, in all cases, be significantly below that of crew and thus no transgression of non-occupational exposure limits is anticipated due to galactic cosmic radiation. (More precise estimates for the U. S. population excluding intercontinental flights

indicate that 25% of the U. S. population making at least one flight per year received an average of 2.8 mrem/year while, 0.005% making at least 25 flights per year received an average of 63 mrem/year¹⁶.)

- The contribution to the genetic pool, i. e. , the total dose received, divided among the entire U. S. population, has been estimated at 0.47 mrem/person/year, well within the recommended population dose of 170 mrem/year¹⁶.

4. SOLAR FLARE EVENTS

In contrast to galactic cosmic radiation, statistical data on the frequency, magnitude, and physical characteristics of solar flares is sparse. Although somewhat erratic, the occurrence of solar flares is strongly correlated with the level of solar activity, which varies in 11 year cycles¹⁷. A useful index of solar activity is the sunspot number, which has been systematically studied by many reliable observers around the world ever since the 18th century, as shown in Figure 2¹⁵. It is known, however, that solar flares most often occur during the rise and decline in the solar cycle due to solar surface instabilities at these times, as demonstrated in Figure 3¹⁵. A statistical analysis of these data applied to the most recent solar cycle predicts that the 21st solar cycle, which began in 1975, will be extraordinarily active¹⁸. The expected maximum in sunspot number occurring in 1978-9 may be as high as 195 as compared with 106 for the most recent cycle. In this respect, the present cycle sequence should be very similar

to the 19th cycle (1954-65), during which the most intense solar flare ever observed occurred February 23, 1956.

The mechanism for radiological dose delivery from solar flare events is similar to that of galactic cosmic radiation except for its time dependence⁵. Typically, x-rays and radio emissions arrive at the Earth coincident with the observed optical

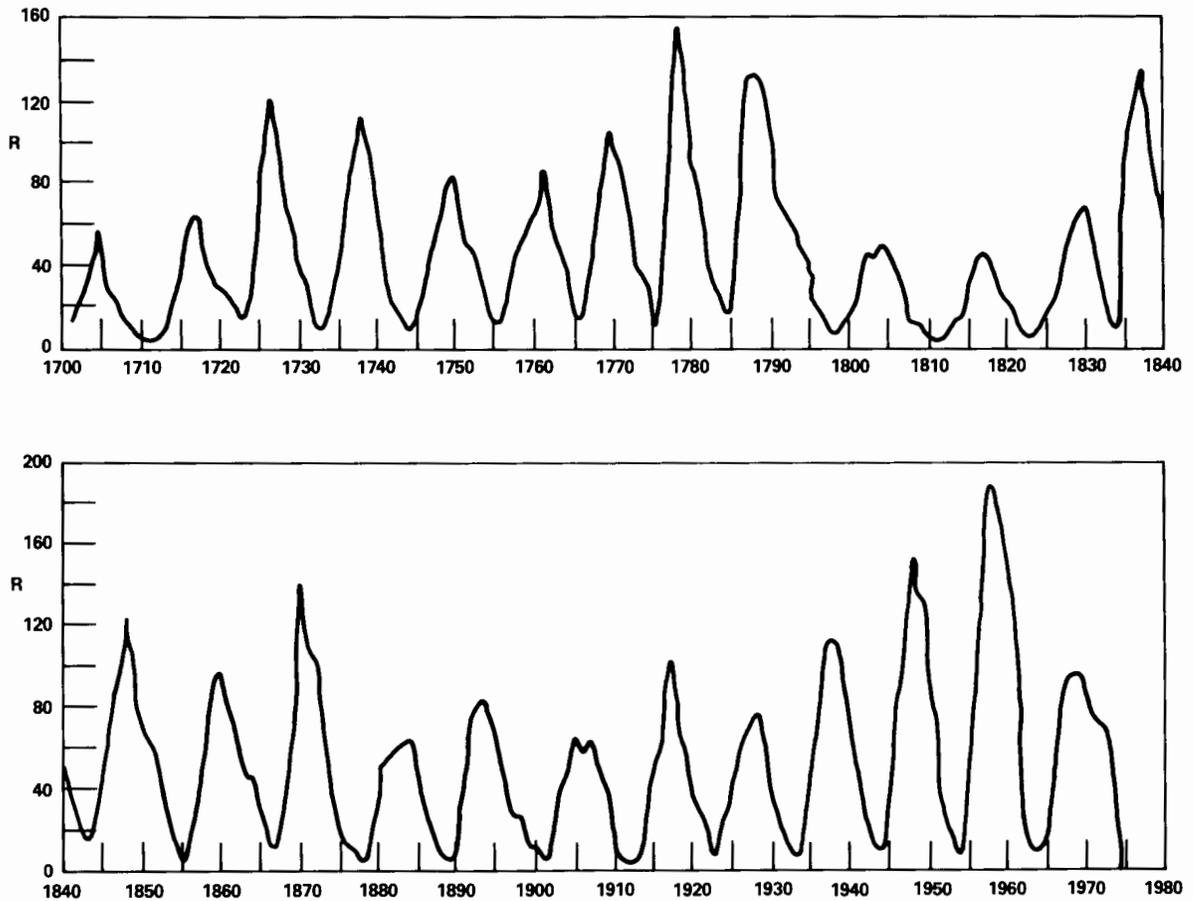


FIGURE 2. ANNUAL MEAN SUNSPOT NUMBER R FOR THE YEARS 1700 TO 1973. (REFERENCE 15)

brightening. Energetic protons begin to arrive as early as 15 minutes to one hour later. The entire sequence of events important for dose considerations

lasts from one to ten hours. The occurrence of multiple sequential flares, as is sometimes the case, represents a special case due to the geomagnetic disturbance caused by the initial flare which allows much greater penetration by subsequent flares¹⁵.

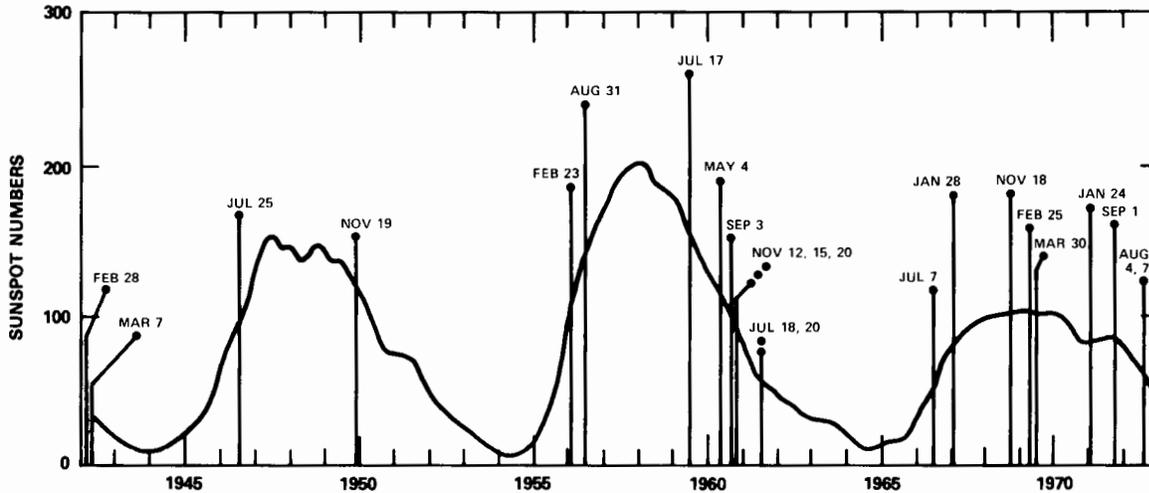


FIGURE 3. RECENT SUNSPOT CYCLES (SMOOTH SUNSPOT NUMBER CURVE) AND SOLAR PROTON EVENTS WITH $E_{\max} \geq 440$ MeV MEASURED AT GROUND LEVEL. (REFERENCE 15)

Instrumental developments capable of assessing radiological doses due to solar flare events has resulted in reliable data only over the last two solar cycles¹⁹. Despite the present deficiency in the statistical data base, some inferences pertaining to the event probability may be drawn. Table 5 tabulates the events of radiological significance since 1956¹⁵. A more detailed altitude resolution for the five major flares is shown in Table 6¹⁵. Insofar as excess doses at subsonic altitudes is concerned, it may be seen that only two events, one occurring each cycle, have been documented. Given that the duration of such events is on the order of several hours, it is highly unlikely that any passengers or

TABLE 5

SOLAR PROTON EVENTS RESULTING IN RADIATION DOSE EQUIVALENT INDEX RATES IN EXCESS OF 10 mrem/hr (CALCULATED FOR 17 km ALTITUDE AND 70°N)^a

<u>CYCLE</u>	<u>YEARS</u>	<u>Dose Equivalent Index Rates in Excess of</u>			
		<u>10</u> <u>mrem/hr</u>	<u>20</u> <u>mrem/hr</u>	<u>50</u> <u>mrem/hr</u>	<u>100</u> <u>mrem/hr</u>
19	1956 to 1964	Total of 8	Feb 1956 Jul 1959 Nov 1960 Nov 1960	Feb 1956 Nov 1960	Feb 1956
20	1965 to 1973	Aug 1972 Aug 1972	Aug 1972	Aug 1972	Aug 1972

^aReference 15

crew could have received a dose in excess of that recommended by NCRP. (In view of the infrequency of these occurrences the ACRB made a study of the relevance of NCRP dose limit recommendations to this special case and concluded that the limit should be interpreted as "500 mrem per flight."¹⁵)

On the other hand both the 1956 and 1972 events might have delivered a dose of 500 mrem to passengers and crew of hypothetical supersonic flights. Thus even

though the probability is small (i. e. , a probability per trip of less than 10^{-3}) the French-Anglo-U. S. SST Committee recommended instrumentation aboard such aircraft that would permit detection of solar flares in progress and allow descent to safer altitudes¹⁵. Operational decision levels adopted by the Royal

TABLE 6

ESTIMATED DOSE EQUIVALENT INDEX RATES AT VARIOUS ALTITUDES FOR MAJOR SOLAR PROTON EVENTS 1956 to 1972^a

Date	Dose Equivalent Index Rate mrem/hr at 17 km	Estimated Altitudes (at high geomagnetic latitudes) Above which the Dose Equivalent Index Rates Exceeded		
		100 mrem/hr	50 mrem/hr	20 mrem/hr
23 Feb 56	500+	Below 12,833 m	Below 11,500 m	Below normal subsonic cruise levels
16 Jul 59	30	Above 21,667 m	19,833 m	16,333 m
12 Nov 60	70	19,167 m	16,500 m	13,833 m
15 Nov 60	40	21,833 m	18,500 m	13,333 m
4 Aug 72	400	13,667 m	12,000 m	Below normal subsonic cruise levels

^aReference 15

Aircraft Establishment are²⁰:

- <10 mrem/hr - no action required
- 10-50 mrem/hr - descent to restore level below 10 mrem/hr if such action can be taken without causing a diversion.
- >50 mrem/hr - either descent or diversion is required to bring level below 10 mrem/hr.

This on-board system has been supplemented by information from the solar flare prediction and warning system located at the NOAA Space Environment Services Center (SESC) in Boulder, Colorado. For the past eight years SESC has issued forecasts of selected variables pertaining to the space environment to 60 U. S. agencies and the SST operators. In addition, warnings or alerts are disseminated to approximately 100 agencies when an event of special concern appears imminent. This capability allows the FAA to anticipate disruption in VHF and HF communications systems which characteristically accompany major solar flare events. Although the FAA currently has no standing operational procedures for restricting subsonic air commerce during solar flare warnings, a study concerning the necessity and feasibility of such special measures¹⁹ has recently been completed and is currently being evaluated.

Despite the demonstrated success of SESC forecasting operations, its utility for general flight planning purposes must also be assessed from a practical viewpoint. Using SST forecasting data (based on radiation levels at 50°N, 50-60,000 ft.)

from April 1971 to June 1973, an avoidance threshold of 10% forecasted probability for levels of 100 mrem/hr would have resulted in a 62% false alarm rate¹⁹. However, this represents only eight days of unnecessary avoidance, whereas all five days of actual hazard during this time period would have been avoided. Such a false alarm rate may be acceptable in this situation.

Thus, from the limited data available, a great deal of concern for the safety of subsonic passengers and crew during solar flare events is evidently unnecessary. While an elaborate instrumentation-forecasting system comparable to that of current supersonic aircraft does not now appear to be warranted, if future developments demonstrate the need for such a system, its implementation would be relatively straightforward. In all cases it should be pointed out that aircraft descent constitutes the most efficient and expedient protective measure²¹.

5. DEBRIS FROM NUCLEAR TESTING

During the 1950-60s extensive atmospheric testing of nuclear weapons by the major world powers gave rise to public concern for a variety of problems associated with debris "fallout" from contaminated air masses. The possibility of the accumulation of radioactive debris on the exterior of aircraft was deemed serious enough to warrant the initiation of monitoring efforts by the aviation industry, including British Overseas Aircraft Corporation²², Pan American Airways²³ and Air India²⁴. Owing to the extreme variability in recorded activity levels and lack of correlative variables, quantitative scientific assessment of the problem

was not achieved. However, no radioactivity reading was found to indicate a real health hazard to passengers, crew, ground personnel, or the general public.

With the advent of supersonic flight, an additional concern arose due to the higher cruising altitudes at which such craft are designed to fly. Characteristically, high-yield nuclear tests which produce enough radioactive debris to present a potential health hazard also result in a debris stabilization height above the tropopause which may intersect typical supersonic flight trajectories, as shown in Figure 4²⁵.

Upon the detonation of a fusion-fission type nuclear weapon (a "hydrogen bomb"), the energy released from the fission chain reaction results in a diverse spectrum of unstable (radioactive) isotopes as a result of nuclear transformation of the bomb casing, the fissionable mass and any contamination of entrained dust or water. Radiological hazards result most directly from atmospheric and ground level tests, although venting from underground tests is also a potential source. Detonations at altitudes of less than two kilometers entrain a large quantity of dust, and ground effects are such that the debris stabilization height is substantially less than that shown in Figure 4. In addition, immediate local-area fallout becomes the predominant removal mechanism and the resulting hazards to aircraft from such detonations are minimal. Air concentrations of debris material depend on the amount of radioactivity produced, its initial vertical distribution, and several localized meteorological variables. The total amount of radioactivity and isotopic distribution are generally proportional to the weapon yield.

Vertical spatial distribution of the debris is dependent on both the weapon yield

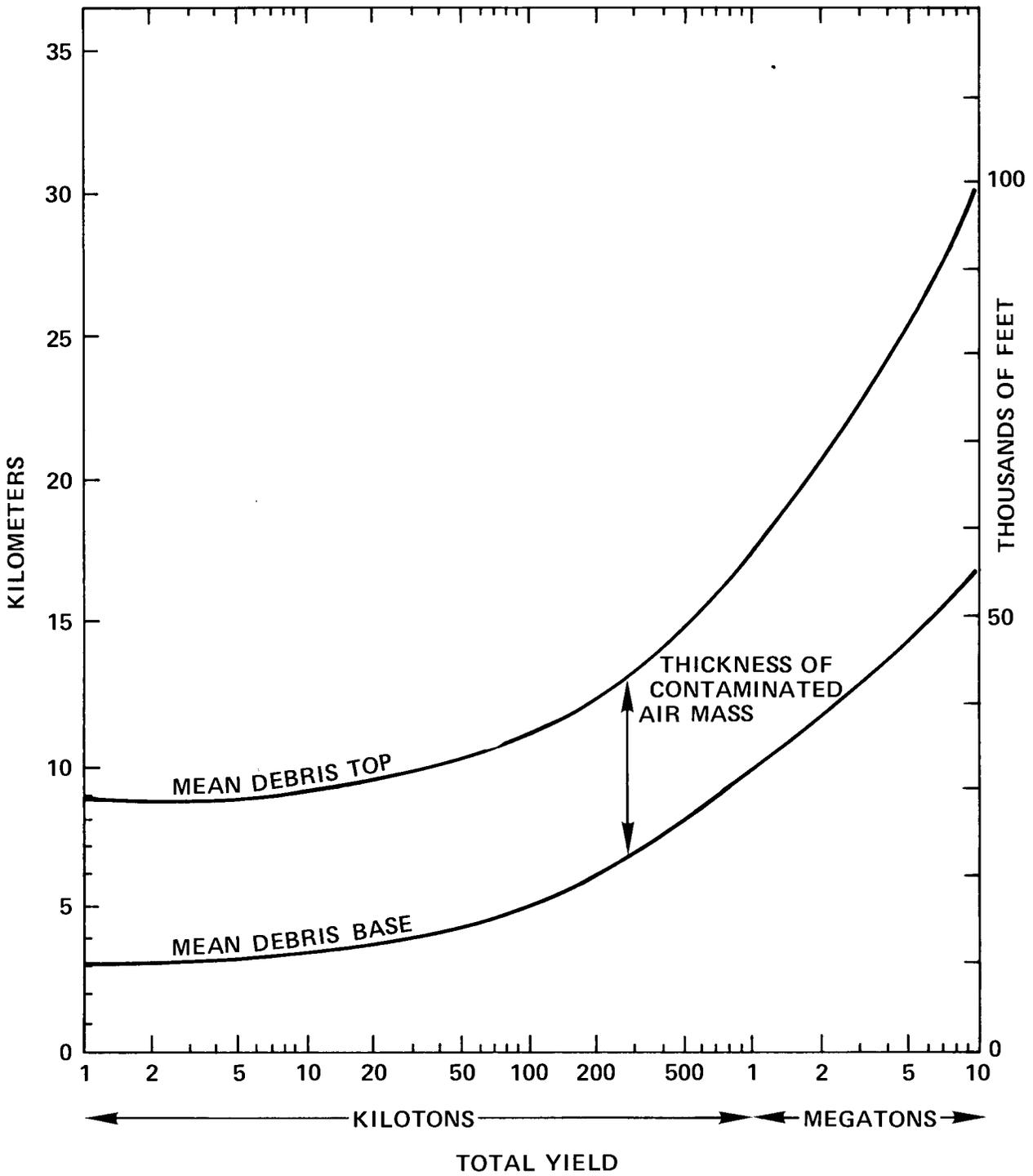


FIGURE 4. MEAN DEBRIS TOP AND BASE AS A FUNCTION OF TOTAL WEAPON YIELD FOR AN AIR BURST. (REFERENCE 25)

and temporal atmospheric structure (tropopause height) known to be seasonally affected. Meteorological factors such as wind speed, horizontal dispersion coefficients, and convergent areas of precipitation scavenging also strongly affect both the geographical location and concentration of the contaminated area. The trajectory of the contaminated air mass is mainly limited to latitudinal transport with some poleward motion since vertical, meridional and quasi-horizontal "diffusion coefficients" in the stratosphere are on the order of 10^4 , 10^9 , 10^{10} $\text{cm}^2 \text{sec}^{-1}$, respectively. Within one day the debris travels several thousand miles, while also spreading laterally. Thus for remote testing sites such as Lop Nor (40°N, 90°E), in the People's Republic of China, the earliest possible encounter times for flights outside China are on the order of 1 to 2 days after detonation. The debris then continues to travel around the globe while natural removal processes become increasingly important. Average lateral diffusion has been observed to dilute the debris activity by a factor proportional to t^{-2} where t is time. Radioactive decay of fission products follows a $t^{-1.2}$ dependence such that center activity of the contaminated air mass is reduced approximately by $t^{-3.2}$.

The concern for potential radiological hazard to man is twofold. First, in-flight ambient radiation levels pose a direct threat to air passengers and crew. The source of this ambient radiation level derives from the component of the debris decay which directly penetrates the aircraft structure. Due to the gaseous nature of some fission products, and particulate debris in the 1μ range which

is inefficiently removed by filtration, an additional potential exists for inhaled and ingested radioactivity possessing both γ and β components. (β -rays generally will not penetrate aircraft skin but may arise from material which comes in through air intakes.) Second, radioactive particles deposited on the structural exterior by impaction present a potential hazard to aircraft maintenance crews and other personnel contacting portions of the aircraft on the ground. This deposited debris material possessing γ and β characteristics may be removable, or to some degree, fixed to the aircraft surface. The potential for detrimental health effects arises mainly from the possibility for transfer of the radioactive contaminant from the hands to the mouth via food, cigarettes, poor personal hygiene habits, etc.

The potential for a radiological inhalation hazard while in transit through a contaminated air mass has not been fully assessed. Major scientific uncertainties remain regarding the physical form of the debris products (e. g. the size distribution of debris aerosols formed through natural processes), the extent to which debris products are removed by the compression and processing of ambient air, and the tendency for possible lung retention of submicron aerosol particulates. A highly conservative estimate indicates that for transit through a one-day old contaminated air mass from a 1 MT atmospheric device (as might be encountered in the Far East, following a Chinese test), a total inhalation dose of up to 600 mr might be accumulated in the respiratory organs — about 20 times that received from transit through the ambient radiation-contaminated environment without

considering inhalation. However, more realistic calculations would likely demonstrate the actual dose to be at least an order of magnitude less than this. Clearly more work needs to be done to properly assess the magnitude of this potential hazard.

Owing to the lack of information concerning the various possible dose-to-man relationships and the many variables which determine air concentrations of nuclear debris, a general assessment is not possible. In order to ensure that no undue risks are taken, the FAA has adopted a policy of debris avoidance until confirmation of the absence of actual hazards is accomplished. Avoidance thresholds have been taken to be the same as those for solar flare avoidance discussed previously.

Nuclear weapons testing was once again recognized as an FAA concern in November of 1976. At that time, the People's Republic of China conducted an atmospheric test of approximately four (4) megatons in yield. Concern over the possibility of contamination of commercial aircraft by airborne debris was expressed at this time by the Environmental Protection Agency (EPA) and public interest groups. In recognition of this problem an ad hoc Radioactivity Task Force was established to deal with the immediate situation and to ensure that all necessary efforts to maintain radiological health standards should continue as a formal function of the FAA. During the period immediately following the November 1976 test, contacts with other Federal agencies were strengthened and a substantial

monitoring effort at several key airports was undertaken. This effort encompassed about a dozen airlines (domestic and foreign), on the order of 1,000 individual measurements of radioactivity levels on aircraft surfaces (exterior and interior) and about 100 hours of in-flight data accumulation on commercial routes (including on-board Concorde measurements). The effort confirmed that no hazard to public health could be established during this event²⁶.

Since that time, a formal network of communications and support has been established with other agencies and a Radioactivity Task Force composed of key FAA personnel possessing a wide diversity of expertise, has been formed. An Inter-agency Memorandum of Understanding outlining specific areas of responsibility has been drafted and at this writing (February 1978), is being reviewed by all other involved Federal agencies. Updated FAA standing operating procedures have been prepared and circulated for comment within affected FAA services.

Inasmuch as FAA concerns are most acute during the early stages of the sensitive period (for example, the intersection of a Chinese debris cloud trajectory with great circle air routes to Japan), timely decisions must be based on predicted cloud locations and activities rather than actual measurements or observations. Typically, field data does not become available until well after many commercial flights would have encountered the cloud. The scope of the Task Force effort has, therefore, been expanded to include the radiological hazard forecasting facility known as the Atmospheric Release Advisory Capability (ARAC) located

at Livermore, California²⁷. This is supplemented by the official National Oceanic and Atmospheric Administration Federal forecasts issued from the Air Resources Laboratory in Silver Spring, Maryland, and other sources. Department of Energy radiological assistance teams can also be deployed on a short notice basis for the purpose of monitoring.

On September 17, 1977, the People's Republic of China detonated its 22nd nuclear test weapon, the yield of which was estimated to be less than 20 kilotons. Although the debris stabilization height was sufficiently low as to pose a potential threat to subsonic craft (see Figure 4), the activity of the contaminated air mass was predicted to be relatively small. It was judged that no altitude or route deviations were, therefore, necessary. Subsequent sampling data confirmed these predictions. Generally weapon yields of about 25 kT or less result in cloud center activities after 24 hours below the avoidance threshold (10 mrem/hr.)

Although all data from past nuclear testing episodes have failed to document any transgression of radiological safety standards, the FAA shall continue operation of the Task Force until an unequivocal determination of the lack of real potential danger to air commerce has been accomplished. Thusfar, a mechanism has been established whereby the FAA can act quickly to avoid any measured or forecasted potential radiological dangers. The FAA is currently in the process of alerting and reminding all field personnel of the possible hazards associated with a contamination incident and continuing its effort to secure the

cooperation of the air transport industry, as well as other Federal agencies in dealing with such events.

6. MISCELLANEOUS

Although three radiological hazards have been identified as recurring problems, a variety of other single-event phenomena have also been recognized in the past. These, by definition, are unforeseeable and require a rapid response by knowledgeable FAA personnel. As an example, it has already been demonstrated that the increasing use of nuclear materials in outer space presents a non-negligible hazard for air commerce.

In early December 1977, North American Defense Command ground-based surveillance instruments in Cheyenne Mountain, Colorado detected aberrant behavior in the orbit of the Soviet Cosmos 954 satellite. When it became apparent that orbital stabilization was not to be possible, ensuing discussions between U. S. and Soviet officials revealed that the craft contained 110 pounds of highly enriched ^{235}U for the stated purpose of providing power for an ocean radar surveillance system. At approximately 6:50 a. m. , EST, January 24, 1978, the satellite entered the atmosphere heading in a north-easterly direction over western Canada.

An adequate assessment of the possibilities for significant (~ 10 mrem/hr) atmospheric contamination required knowledge of several critical parameters:

- The degree of isotopic enrichment, configuration of the radioactive mass, and the approximate power output;
- The altitude and extent of ablation and burn up;
- The location of entry; and
- The synoptic meteorological patterns at time of entry.

Reliable data were immediately obtainable in this case only for the latter two requirements. In the absence of generally available knowledge with regard to the first two points, conservative assumptions were made for contingency planning purposes.

The reported ^{235}U mass was most probably configured to perform as a conventional fission nuclear reactor. This imposes substantial weight and design restrictions for typical satellite payloads in which required power levels must be compromised with operating lifetime. Generally, a greater mass of control material (neutron absorber) and moderator retards the fission chain reaction, such that the core may have a relatively longer lifetime at a relatively lower power level. Conversely, a smaller mass of control material and moderator results in higher power levels, shorter lifetime, and implies a less restrictive weight limitation.

The level of activity is primarily due to the buildup of secondary fission products such as $^{131-135}\text{I}$, ^{90}Sr , ^{137}Cs , and ^{85}Kr which have shorter half-lives and more energetic radiation. The steady state amount of secondary fission products is

directly related to the rate of ^{235}U fission and is thus proportional to the power level by empirical formulations.

Although U. S. satellites now depend primarily on solar energy, early prototypes in the 1960s utilized radioactive heat sources of ^{238}Pu (called the "SNAP" power generator). The heat produced by natural radioactive decay was efficiently converted into useful energy by highly advanced thermocouples. Thus, the more dangerous fission products characteristic of a ^{235}U reactor were not present. In addition, the predominant radiation from ^{238}Pu is an alpha particle of extremely low penetrating power. Therefore, when such a satellite burned up in the upper atmosphere in 1964, no radiological hazard existed. However, the fate of the radioactive debris was carefully assessed by the (then) Health and Safety Laboratory of the (then) Atomic Energy Commission and valuable data were gathered concerning the atmospheric removal processes important for such high altitude injections.

Through observations of previous Cosmos prototype lifetimes, two to three months, and the stated mass of ^{235}U it was deduced that the power output of such a configuration was roughly 100 kilowatts. This would result in an initial activity of approximately 1×10^5 Curies (Ci) at the time of burnup, equivalent to a dose rate of 2-3,000 mrem/hr at hypothetical cloud center. Using this as an operational assumption, calculations were performed by the Atmospheric Release Advisory Capability Center to estimate the most conservative (i. e. pessimistic) limits of atmospheric contamination. The results of this exercise indicated that after one day the cloud center dose rate was less than one microrem/hr at flight altitude, or about 400

times less than the level of galactic cosmic radiation at that latitude. Dose rates in excess of 10 mrem/hr could only have been experienced within two hours of burnup.

In addition to the foregoing considerations of cloud center activities, a full assessment of the problem must also take into account the altitude at which ablation and burnup occur. In general, with increasing altitude of burnup, the removal time (and, implicitly, the time for the debris to reach flight altitudes), becomes disproportionately longer. For example, inert stratospheric tracer lifetimes above 20 km are on the order of one to two years. At altitudes below five km, the residence time is on the order of two to ten days. The intermediate range of altitudes have highly variable residence times which are functionally dependent on meteorological conditions. Although the 1964 SNAP-9A burnup occurred at roughly 40-50 km and debris was not detected at flight altitudes for several months, the ARAC estimates used in the case of Cosmos 954 conservatively assumed burnup between 6 and 16 km with debris center located at 11 km.

It is worth noting that the U. S. and Soviet designs of safeguard mechanisms for such events differ markedly. United States nuclear satellite packages are encased in steel and coated with an ablative ceramic layer which burns off upon entry. This enables the entire nuclear package to survive its 17,000 mph transit through the upper atmosphere and impact. Soviet nuclear materials, however, are designed to burn up in the upper atmosphere, presenting a relatively greater potential hazard to aircraft. It is not clear at this writing whether the Cosmos 954 package did, in fact, burn up or survive its entry. Thusfar, atmospheric

sampling efforts have revealed no presence of measurable activities, and no hazard to air commerce was predicted (or found) to exist.

7. CONCLUSIONS

In summary, Table 7 lists the most significant natural and anthropogenic radiological health hazards to man based on U. S. population statistics. Although, as seen, air transportation could contribute somewhat more than other sources, the total dose received is nevertheless far below recommended dose restrictions²⁸. Population doses from aviation constitute an insignificant fraction of all radiation received²⁹.

On the basis of the statistical relationships hypothesized by the National Academy of Sciences, ACRB has estimated that for a population dose of 1×10^8 mrem-man/year the increase in the genetic mutation rate will fall between 0.0014 and 0.014 percent¹⁶. Allowing for natural recovery processes, these estimates may be reduced by a factor of five or more. Somatic effects, then, may result in two to five earlier cancer deaths per year in a population of 225 million. These effects would be undetectable against the natural background of genetic mutations and cancer mortality.

This fatality rate represents an individual risk of 5.0×10^{-7} (i.e., five chances in 10,000,000) for the average airline passenger and 1.0×10^{-5} for the frequent airline passenger (more than 25 flights/yr). Airline flight and cabin crew risks

TABLE 7

COMPARISON OF TYPICAL RADIATION LEVELS

<u>Location or Source</u>	<u>mrem/hr</u>	<u>Dose Equivalent mrem/year</u>	<u>mrem-man/year (U.S.)</u>
Mid-Atlantic ^a	.006	55	—
Guarapari Brazil ^a	.14	1200	—
Average Natural Radiation (ground level) ^b	.01	130	2.6×10^{10}
Fallout from Atmospheric Testing ^b	5×10^{-4}	4.4	1.1×10^9
Color Television ^{a,b}			
Close to Set	.5	—	3×10^7
Six-Foot Distance	.01	—	
Luminous Watch ^b	$1-5 \times 10^{-4}$	1-5	2.4×10^{10}
Medical ^b	—	—	1.5×10^{10}
33 Cosmic Radiation ^c			
Subsonic Flight	.2-.3	{ 2.82 (passenger) 160 (crew)	9.9×10^7
Supersonic Flight	.75-1.3	300-600 (crew)	—
Solar Flares ^c			
Subsonic Flight	{ 100 (no avoidance) 10-50 (avoidance)	{ 100 (no avoidance) 10-50 (avoidance)	5×10^6 (no avoidance) —
Supersonic Flight	{ 500 (no avoidance) 10-50 (avoidance)	{ 500 (no avoidance) 10-50 (avoidance)	— —
Nuclear Testing	10-50 (avoidance)	10-50 (avoidance)	

^aRef. 28^bRef. 29^cThis report and references contained herein.^dDraft of Standard Operating Procedures, Radioactivity Task Force

are approximately 2.9×10^{-5} . In Table 8 these figures may be compared with those incurred (and implicitly valued) in various recreational pursuits, occupations, and miscellaneous daily activities.

More work needs to be done to accurately assess potential radiation hazards from inhalation of debris products soon (one or two days) after detonation (as might occur, for example, in the Far East, for Chinese weapons tests) of a nuclear weapon.

It is clear that a risk-free society is an unachievable goal. Daily risks which are accepted, either implicitly or explicitly, dwarf those resulting from added radiation exposure from air travel. Wherever possible, however, it is the policy of the FAA to eliminate or, at least, minimize all potential risks if no greater risks would be incurred by that avoidance and if the act of minimization can be done without disproportionate economic hardship.

TABLE 8
COMPARISON OF COMMON RISKS^a

Activity	Risk of Death x 10 ⁻⁵ per year
Recreational:	
Motorcycle Racing	1,800
Horse Racing	1,300
Auto Racing	1,200
Sunbathing (curable skin cancer)	500
Power Boating	170
Rock Climbing	100
Canoeing	40
Football	4
Skiing	3
Amateur Boxing	2
Drowning (all recreational causes)	1.9
Fishing (drowning)	1.7
Occupational:	
Coal Mining (Black lung disease)	10,000
Coal Mining (accident)	1,500
Fire Fighters	1,000
Railroad Workers (accident)	400
Steel Workers	60
Airline Crewmembers (accident)	50 ^b
Manufacturing (Total)	5
Airline Crew Members (Radiation)	2.9 ^d
Miscellaneous:	
Fatal Fall	7.7
Poisoning	
Gases and Vapors	0.7
Solids and Liquids	0.6
Electrocution	0.5
Airline accident	0.3 ^c
Air Transportation (Radiation)	
Frequent Passenger	1.0 ^d
Average Passenger	0.05 ^d

^aFrom Reference 30 unless otherwise indicated

^bAnalysis of data available from the National Transportation Safety Board indicates that this risk is 30×10^{-5}

^cAnalysis of data available from the National Transportation Safety Board indicates that this risk is $.2 \times 10^{-5}$

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