RADIATION MEASUREMENTS AND DOSES AT SST ALTITUDES

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A brief survey of results up to 1970 of an experimental and theoretical study of biologically important radiation components and dose equivalents due to galactic and solar cosmic rays in the high atmosphere, especially at SST altitudes, is presented.

The dose equivalent rate for the <u>flight personnel</u> flying 500 hours per year in cruise altitudes of 60,000-65,000 feet (18-19.5 km) in high magnetic latitudes turned out to be about 0.75-1.0 rem per year averaged over the solar cycle, or about 15-20 percent of the maximum permissible dose rate for radiation workers as established by the International Commission on Radiological Protection (ICRP) for peacetime operations (5 rem per year).

The gross of <u>passengers</u>, who do not encounter major solar events, would be exposed only to the low level galactic cosmic rays. Such exposure would amount to some mrem per North-Atlantic trip and is therefore negligible. Very rarely, groups of passengers, who happen to be passing through the impact zone of a rare giant solar event such as that of February 23, 1956, would be exposed to 0.45 rem, provided the airplane descends to subsonic altitudes at the beginning of the event and continues its flight at the lower altitudes. This exposure, 0.45 rem, is 90 percent of the permissible limit for individuals of the general population (0.5 rem per single year). At cruise altitude, the maximum permissible limit would have been surpassed. The suggested evasion measure of descending to lower altitudes is therefore sufficient to avoid overexposure of passengers in such rare cases.

I. INTRODUCTION

There has been continuing concern about the radiation safety in airplanes such as the SST. The high-altitude commercial airplanes, as they are envisioned for the future, will cruise at altitudes of 60,000 to 65,000 feet (18-19.5 km). At such altitudes, only about 6 percent (about 60 g/cm^2) of the mass of the atmosphere is left above the airplane, which may grant little protection against space radiation such as galactic and energetic solar cosmic rays. In fact, the nuclear reactions of the cosmic rays within this upper 6-percent of the atmosphere produces many secondaries, including the particularly biologically effective neutrons whose net biological effect may exceed that of the primaries.

In the following the author may review what we know of this problem - mainly as it concerns the radiation exposure of the crew and passengers at SST and lower altitudes - and what evasion measures might have to be taken during times of energetic and intense solar particle events.

II. DATA SOURCES

Our understanding is based to a large extent on Langley high-altitude experiments with high-altitude balloons and airplanes measuring cosmic rays and their variations with solar activity, from 1965 to the present, over a large part of the solar cycle (refs. 1 and 2).

Figure 1 is a brief review of these data sources. Through the 4 years from 1965 to 1968, 20 balloon launches, five each year, were conducted by Langley from Fort Churchill, Hudson Bay, Canada. From 1968 to the present, about 300 U2 and RB57-F flights from London, England; Maine, USA; and Eielson AFB, Alaska, have been made. The latter in cooperation with the Air Force and FAA. We owe particular thanks to the Air Force for its generous cooperation. Spot checks in lower latitudes were conducted with balloons from Heiderabad, India, and from Pallestine, Texas. Furthermore, five latitude scans with RB57-F's from Eielson AFB, Alaska, to Albuquerque, New Mexico, and down to the equator were made. A complete latitude scan at 35,000 feet was conducted by participating in the 65-hour globe-circling flight over both poles with a Boeing 707 airplane in 1966.

We note that most flights were made in high magnetic latitudes. The reason is that we are mostly interested in maximum doses and these occur at latitudes above $\approx \pm 50°$, which contain the North Atlantic and Canadian routes and possibly routes from Moscow to the U.S.A. Below 50° magnetic latitude, the doses fell off rather rapidly because the magnetic field of the Earth deflects the cosmic ray particles at the lower latitudes. The dose rates decrease by about a factor of 6 toward the equator, according to our measurements. Thus, precautionary measures would not be necessary on the Pacific and Southeast Asian routes.

Additional relevant data include ground experiments and extensive theoretical analyses made at Oak Ridge National Laboratory in an 8-year study (refs. 3-8) and at Langley (refs. 9-13) applying the developing dose calculation methods to the accumulated spectral data on solar events, especially those of the highly active solar cycle 19 (1954-1964) and extending the Oak Ridge Laboratory methods to higher energies.

III. MAXIMUM PERMISSIBLE DOSES

Before reporting on measurements and relevant results, it may be well to recall the biological doses which are internationally accepted as maximum permissible doses (MPD's) for peacetime operations and their definitions.

In figure 2, applicable MPD's, as established by the ICRP, are briefly summarized.
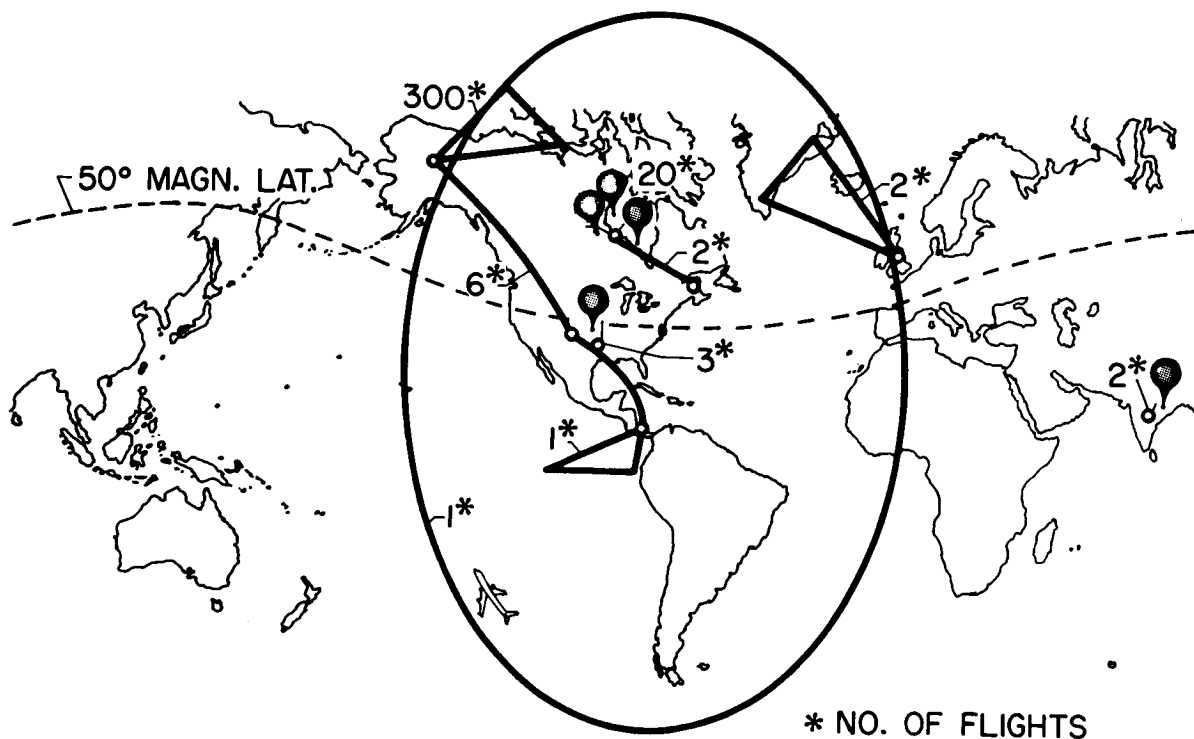
HIGH ALTITUDE RADIATION MEASUREMENTS
1965 – 1971

The doses are given in rem, which stands for "roentgen equivalent man" and is different from rad which measures only the energy absorbed per gram. For a given amount of absorbed energy, heavily ionizing nuclei and neutrons do much more biological damage than X-rays or electrons or other lightly ionizing particles. When the dose is corrected for this increased biological effectiveness, we have the rem. For example, for fast neutrons as we encounter them in high altitudes, the dose equivalent or rem is about 10 times their absorbed dose.

We note in figure 2 that the average MPD for radiation workers is 10 times higher (5 rem per year) than the MPD for individuals of the general population in a single year (0.5 rem per year). The reason is that radiation workers are a small group of adults. The general population encompasses children, including infants - even the fetus in pregnant women - who are much more sensitive to radiation. In fact, the guidelines for the general population are even more restrictive. "Total of 5 rem to age 30" means that in the average to age 30 only 0.167 rem per year is permissible. Thus, 0.5 rem is not allowed for every year.

MAXIMUM PERMISSIBLE DOSES (MPD'S)

RADIATION WORKERS: WHOLE BODY	$\dfrac{5 \text{ rem}}{\text{yr}} = \dfrac{0.6 \text{ mrem}}{\text{hr}}$
POPULATION: INDIVIDUAL	$\dfrac{0.5 \text{ rem}}{\text{yr}}$ (TOTAL OF 5 rem UP TO AGE 30)

For high altitude flight, we equate the crew or flight personnel to the radiation workers because they are adults; and we equate the passengers to the general population. Thus, we may note the following two numbers:

For the crew	5 rem per year on the average over long periods, say 10 to 30 years, are permissible
For passengers	Maximum 0.5 rem per year in single years, or one time in a single year, is considered permissible.

IV. MEASUREMENTS AND DERIVATION OF THE DOSE EQUIVALENT RATES WITHIN THE ATMOSPHERE

The following describes the measurements which were made and how the dose equivalent rates were obtained from measurements and theoretical calculations. As mentioned before, one of our main concerns has been the contributions of the fast secondary neutrons to the dose equivalent rate in SST altitudes, which were unknown in wide limits. Figures 3 and 4 illustrate the problem.

Figure 3 shows, schematically, the incoming galactic and solar light and heavy nuclei, which interact in nuclear collisions with the air atoms, mainly in the first 30 g/cm^2 of air that is above 80,000 feet. In their collisions, the primary particles produce secondaries which, on their part, again produce secondaries in further nuclear collisions, and so forth. Figure 3 shows only the produced neutrons and shall indicate that the produced neutrons penetrate relatively freely, that is, without substantial energy loss, deeply into the atmosphere. Being neutral particles, they lose no energy by ionization. The neutrons have a mass which is by a factor of about 15 lower than that of the air atoms O and N and lose, therefore, also little energy at elastic collisions. In fact, at low energy solar events (E ≤ 200 MeV/nucleon) essentially only a neutron increment is found in SST altitudes, because the charged primaries come to rest by ionization or are fragmented in nuclear interactions - their charged secondaries coming to rest by ionization in higher altitudes.

NEUTRONS IN AIR

NEUTRONS IN TISSUE
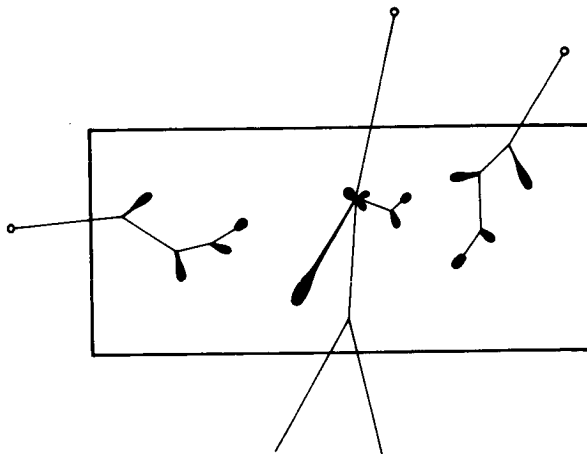
Within the hydrogen containing tissue of man's body, however, the neutrons are most biologically effective, as indicated in figure 4. In tissue they are strongly absorbed in losing, on the average, half of their energy in every elastic collision with protons (H); which protons, in turn, are charged and produce the heavily ionized recoil tracks, being highly biologically damaging. In the midst of figure 4, a so-called "star" or nuclear interaction with a C, N, or O atom of tissue is indicated with prongs of heavier (biologically effective) and lighter fragments.

Because of their possible importance and the large uncertainty of fluxes and energy spectra, the neutrons were measured separately in the Langley program with a special neutron spectrometer developed and maintained by Dr. R. Mendell, New York University. The detection of neutrons with this instrument is based on discrimination of pulse shapes in a liquid scintillator surrounded by a plastic scintillator, the latter for exclusion of charged particles (refs. 14 and 15).

Besides neutrons - protons, mesons, and photon-electron cascades penetrate to SST altitudes. To determine the doses produced by these more lightly ionizing particles, a tissue equivalent ion chamber which was designed and built by AVCO, Oklahoma, and supplemented with a recorder and maintained by Dr. R. R. Adams, Langley Research Center, was used in the flight experiments. The neutron spectra and tissue absorbed dose were measured with these instruments. They were first suspended in free air and then inside spherical phantoms of tissue equivalent material representing man's body, to derive the dose equivalents in extremities (small tissue sample represented by the sensors) and in the depth of the body.
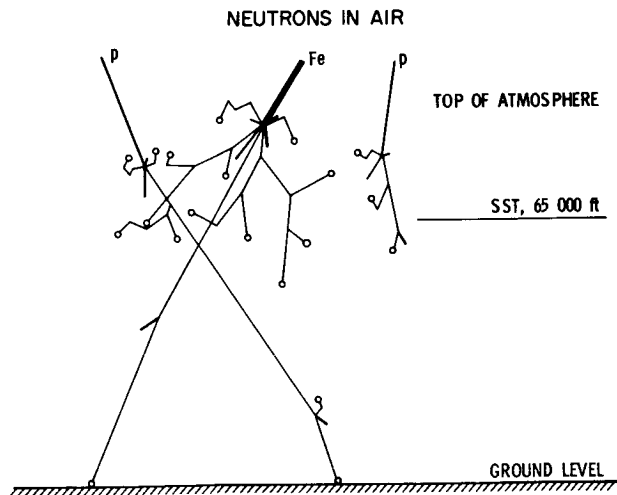
From the neutron spectrum, the absorbed dose rate (rad) and dose equivalent rate (rem) due to neutrons have been calculated by using the flux-to-dose conversion and quality factors defined by the ICRP for neutrons up to 10 MeV energy, and extended by Oak Ridge National Laboratory to neutrons and protons up to 400 MeV. It must be mentioned here that the spectrometer measures only the neutron spectra in the energy range 1–10 MeV. These measurements were used to normalize the total spectra from 0.1–400 MeV obtained by J. W. Wilson (ref. 13) who succeeded in developing a nuclear cascade and transport computer code for incident protons up to 10 GeV (see also ref. 10). The neutrons 10–400 MeV produced by galactic cosmic rays have been found to contribute substantially (about 40 percent) to the neutron dose equivalent rate in high altitudes.

Besides by neutrons, highly biologically effective stars are produced in tissue by primary and secondary charged particles, in particular, protons at SST altitudes. Their contribution to the dose equivalent rate is calculated by taking into account the measurements in tissue equivalent emulsions of Davison (ref. 16).

The total dose equivalent rate is obtained by subtracting the absorbed doses due to neutrons and due to charged-particles-produced stars from their dose equivalents (rem - rad) and adding the ion chamber dose which measures both the absorbed dose due to lightly and heavily ionizing or damaging particles (the latter neutrons, stars). The dose equivalent rate derived in this way is due to all lightly ionizing primaries and secondaries and due to neutrons and charged-particles-produced stars in tissue.

Heavy primary hits or penetrations and heavier fragments than protons produced in nuclear inter-actions with air are neglected. According to meas-urements of Yagoda (ref. 17) and also unpublished measurements in the course of the Langley program, the fluxes of heavy primaries and of energetic heavy fragment are practically zero in 60,000 to 65,000 ft altitude (> 60 g/cm^2 air shielding). The same result with respect to heavy nuclei have theo-retical estimates of H. Schaefer (ref. 18).

### IV. MAXIMUM EXPOSURE OF SST OCCUPANTS AND COMPARISON WITH MPD's

To obtain the maximum exposure of SST occupants and compare these with the MPD's, some of our results on galactic and solar cosmic ray dose rates in SST and subsonic altitudes and at high latitudes will now be presented. We begin with:

1. Galactic cosmic ray dose rates

Galactic cosmic rays are of low intensity; however, they are always present. Their intensity varies by a factor of about 2 in the high-energy range and a factor of about 4 in the low-energy range during the 11-year sunspot cycle.

In figure 5, the circles show the measured dose rates as a function of altitude. The scale is on the right-hand side and is given in rads - not corrected for biological effectiveness. This dose rate is nearly constant above SST altitude in the year 1967. The squares show the fast neutron flux measured separately. The scale is on the left-hand side.

GALACTIC COSMIC RAYS
FORT CHURCHHILL BALLOON TO 43 km (140 000 ft), JULY 15, 1967
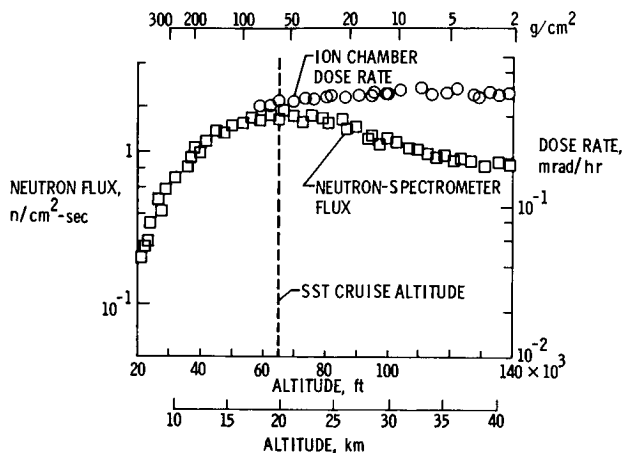
One recognizes that the neutron flux has a maximum just at SST altitudes.

Figure 6 shows the biological dose rates of dose equivalent rates in mrem per hour derived from these measurements.

Consider first the light lines labeled 1965. The dashed curve shows the contribution mainly of the lightly ionizing particles; the dotted line shows the contribution rem-rad of the neutrons; and the x's show the contribution rem-rad of the stars produced by charged particles which are the sites of nuclear reactions, with extensive local damage to the cells (as the stars produced by neutrons). We may mention that the dose equivalent rate due to neutrons, as derived from our measurements and cal-culations, is about four times higher than that estimated in the ICRP task group report of 1966 (ref. 19).

The light solid line is the total dose equivalent rate as function of altitude, which indicates again a maximum at SST altitude. It may be noted that the curve is labeled 1965. That was near sunspot minimum of the solar cycle, when the galactic cosmic ray flux is a maximum. The average over the 11-year solar cycle would be less — about as shown by the heavy line. The average dose rate is about 1.2 mrem/hour at SST altitude.

We obtain, thus, the following results: If the crew flies 500 hours/year in cruise altitude, their average dose rate due to galactic cosmic rays would be about 500 x 1.2 mrem/year = 0.6 rem/year or only about 12 percent of their maximum permissi-ble dose rate.

The gross of passengers, who may cross the North Atlantic only a few times a year, not encoun-tering solar events, would be exposed in 2 hours at cruise altitude to only about 3 mrem, which is neg-ligible in comparison with 500 mrem or 0.5 mrem, which is their permissible limit.

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ENERGETIC SOLAR EVENTS MEASURED ON THE GROUND AND AT SST ALTITUDES
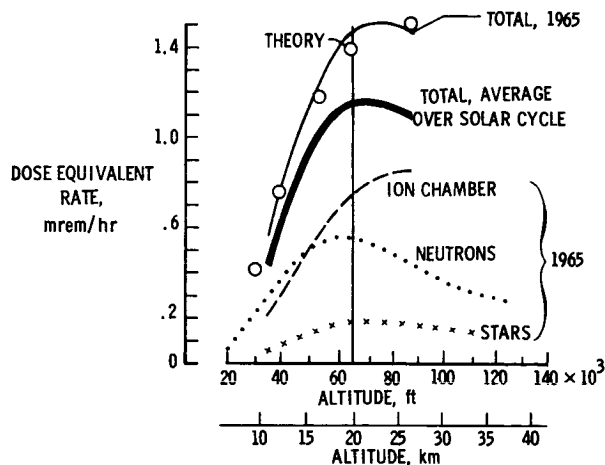
The circles labeled "theory" on the total dose curve for 1965 were calculated starting from the known cosmic-ray spectrum in space, using the mentioned Langley developed computer program, to determine the dose at various depths in the atmosphere. The fairly good agreement with the measurements suggests that such a computer code may be useful to monitor the dose rate in SST's with fair accuracy from the primary spectra measured, for example, in synchronous satellites far out in space, without having instruments onboard the SST's.

2. Solar cosmic ray doses

Solar cosmic rays or solar particle events, accompanying some - but not all - flare outbursts on the sun, are transient particle showers (duration 8-24 hours); however, in some cases, they may have 1000 times higher intensity than galactic cosmic rays.

In figure 7 the two curves on the left correspond to a high-energy event of very low intensity that occurred on March 30-31, 1969. The intensities (ordinates) are plotted against time in hours (abscissa).

The neutron monitor on the ground showed only a 5-percent increase over its background; the latter due to the steady flux of galactic cosmic rays. Our airplane flying at SST altitude, however, showed about a 90-percent increase in biological dose rate or nearly 20 times as much. The factor 20 is somewhat obscured by the log scale on the ordinate, however, the log scale is needed to present in the same figure the much higher increments observed in 1956 at a very intense high-energy event.

The event on the right is the famous giant event of February 23, 1956, which is the largest event observed for at least 30 years. Instead of 5 percent, an increase of 3600 percent on the ground, or 36 times galactic cosmic-ray background was observed. No measurements at altitude could be made in 1956; however, if we use the same factor of about 20 that we found for the smaller flare, we get an increase of 720 times that of March 1969, which represents a dose rate of 1000 mrem/hour or 1 rem/hour at the beginning of the event.
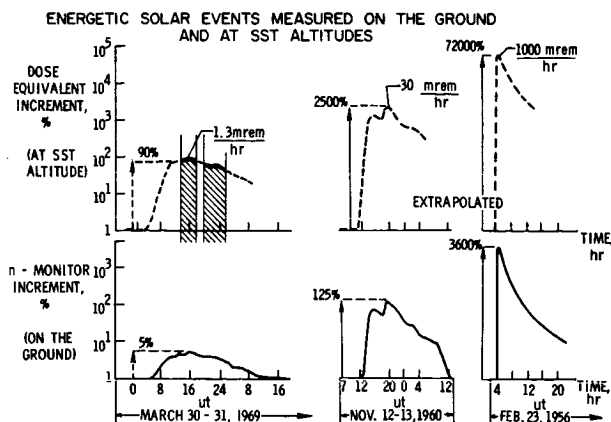
Since the dose that would be accumulated during, say, 2 hours at cruise altitude is apparently above the permissible limit for passengers, it is very important to confirm this high dose rate in any possible way. We started with the fluxes and spectrum above the atmosphere in space which were estimated by Meyer, Parker, and Simpson from ground measurements over a wide latitude range at that time (refs. 20-22) and applied our computer program mentioned earlier.

The prompt spectrum supplemented by estimates of other authors (ref. 12) is presented in figure 8 right.

Figure 9 shows the result of these dose calculations for different altitudes. The maximum dose equivalent rate for February 1956 at SST altitude is found between 3 rem/hour and 0.5 rem/hour, which is in fair agreement with figure 5. The large difference between the upper and lower limit is mainly due to the uncertainty in the lower energy part of the prompt spectrum (< 1 BeV) which could not be measured in 1956.
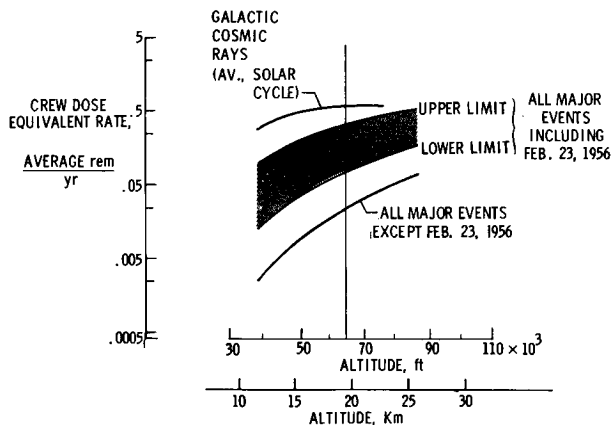
We have made similar dose calculations for the most significant of the 60 solar events of the particularly active solar cycle 19 starting with the energy spectra in space composed from balloon, rocket, satellite, riometer, and scattering network data. The second largest event was that of November 12-13, 1960, which is seen at two different times in figure 9. The dose equivalent rates are only in the order of 30-50 mrem/hour at altitude.

On the basis of these measurements and calculations on solar events, we may again first draw conclusions on the average exposure of the crew from solar cosmic rays assuming, conservatively, that the crew passed through each major event of cycle 19 in its maximum phase. The result is given in figure 10.
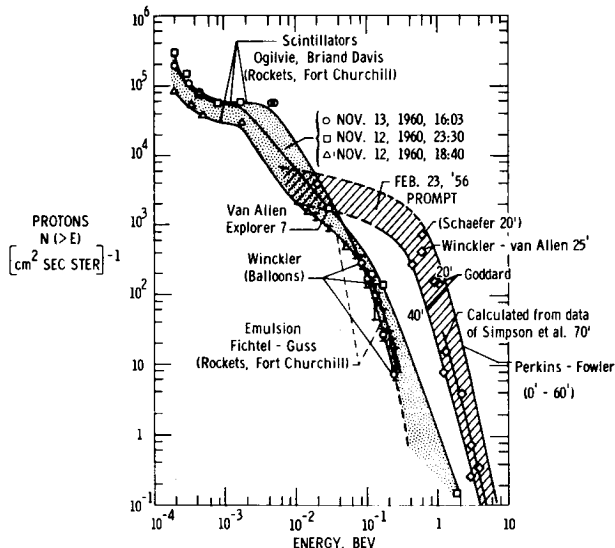
One sees that the contribution of all major events, except that of February 1956, is very low. If one includes the February 1956 event, one obtains an upper limit of 0.3 rem/year as the average

contribution per year from solar events of one cycle. Of course, in none of the single years was the maximum permissible dose rate of 5 rem/year for the crew reached, even if the airplane were to stay in cruise altitude during the events. In adding the previously given galactic cosmic-ray average dose rate of 0.6 rem/year, we arrive at 0.9 rem/year from solar plus galactic cosmic rays. This is the average over the solar cycle and is only 15 to 20 percent of the maximum permissible exposure for radiation workers. We should add here, for correctness, that this exposure on high latitude routes is nevertheless somewhat higher than the actual exposure of 90 percent of the radiation workers in the nuclear industry, which is of the order of only 10 percent of the MPD for radiation workers.
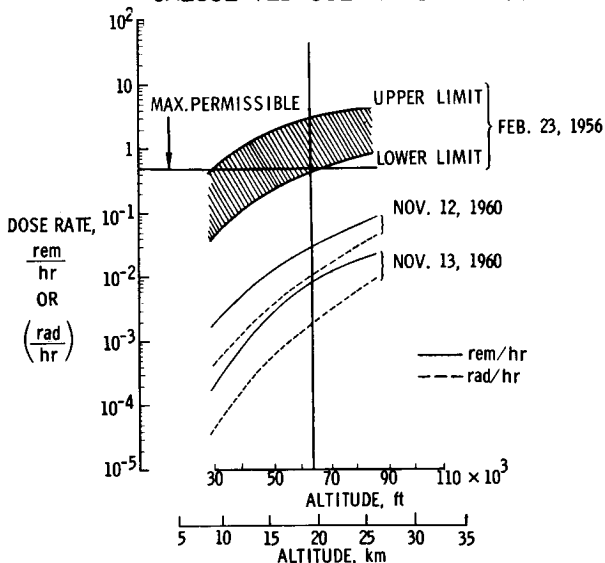
FLARE-PARTICLE SPECTRA

The numbers 20', 25', ... are the minutes after solar cosmic ray onset, observed on earth 0350.

CALCULATED SOLAR FLARE DOSES

GALACTIC AND SOLAR COSMIC RAYS AVERAGED OVER IO-YEAR DUTY

We come now to the most important result so far, namely, that to the best of our knowledge, the permissible exposure of passengers is exceeded if the SST flies at its cruise altitude during such giant events as that of February 1956. This would be contrary to the internationally accepted radiation protection guidelines.

On the other hand, fortunately, atmospheric attenuation is sufficient so that, by timely descent to subsonic altitude during such events, the conservatively high estimated accumulated dose would have been below 0.5 rem, or _below_ the MPD for passengers. We see in figure 9 that the maximum dose rate at 30,000 feet altitude would have been 0.45 rem/hour. This is the dose rate at the peak of the event - of about 10 minutes' duration. This dose rate fell off very fast in the first hours (as in all highly intense energetic events observed so far). The accumulated dose for the first 3 hours, about the maximum time that the SST would remain at subsonic altitude, would not be more than 0.45 rem. Thus, such an evasion measure is _sufficient_ to keep the dose within safe limits in such rare cases.

Furthermore, it appears that in all the other of the approximately 60 solar events such evasion would not have been necessary in order to comply with the requirement to stay below the maximum exposure limit of 0.5 rem, because the maximum dose rate even for the November 12, 1960, event was only on the order of 30-50 mrem/hour at SST altitude. Since it is desirable to hold any exposure as low as possible, one may descend also in such cases, that is, if a level of 50 mrem/hour or even less is reached. Even when evasion in such cases is included, solar cosmic radiation will only in rare cases interfere with the normal operation of the airplanes, since only three more events comparable in size and energy to the November 12 event were observed in the highly active cycle 19.

A design requirement for evasion to subsonic altitude is that the airplane has sufficient subsonic flying capability to reach the next airport from every point of its route. The latter capability was specified for the American SST and is probably specified for the Concorde and the Russian SST for safety reasons. It may be emphasized that an

in-flight radiation warning and monitoring system is required to minimize evasion measures or interference with the normal operation of the SST planes. Other precautionary measures such as delaying flights or rerouting the airplanes to lower latitudes in case active regions on the sun are about to erupt would interfere considerably more with the economical operation of high-altitude aircraft, since as yet, even experienced forecast centers cannot predict if and when such regions erupt and if high-energy particles are produced with high intensity. Only very rare intense high or medium energy events require evasion measures. Giant events comparable to that of February 23, 1956, have occurred only one to two times per 11 year cycle in the past three decades.

V. SUMMARY ON RADIATION EXPOSURE AND SAFETY MEASURES

We may now finally summarize the obtained results on radiation exposure and safety measures (see fig. 11).

1. The maximum exposure of the crew due to galactic and solar cosmic rays, as listed in the upper half of the table, is found to be 0.75-1.0 rem/year averaged over the solar cycle or 15 to 20 percent of the maximum permissible dose rate for radiation workers. This is, of course, also the exposure of passengers who fly as often as the crew on high latitude routes such as, perhaps, executives of airlines, who are presumably adults and would take no significant radiation risk either.

2. The gross of passengers, who do not encounter major solar events, would only be exposed to the low-level galactic cosmic rays. Such exposure would amount only to some mrem per trip and is therefore negligible. A small group of individual passengers, passing such rare giant solar event as that of February 1956, would be exposed to maximum 0.45 rem, which is 90 percent of their permissible limit per year, if the airplanes descend in time and continue the flight at subsonic altitudes during the event.

From the preceding considerations, we come to the following conclusions:

1. If the suggested precautionary measure of timely descent or other evasion measures can be taken in case of giant solar events, radiation appears to pose no hazard to the health and safety of passengers and crew in commercial SST flight - assuming, of course, the validity of the present internationally accepted exposure limits, especially for pregnant persons, for which case there still exists some uncertainty.

2. If a radiation monitoring system exists which indicates to the pilots in time when to descend to subsonic altitudes, and if the pilots can reach the next airport at subsonic altitude, cosmic radiation will only in very rare cases interfere with the normal operation of high-altitude aircraft.

	EXPOSURE	PERCENT OF MPD'S
CREW: (>55° MAGNETIC LATITUDE, AVERAGE OVER SOLAR CYCLE)	0.75 TO 1 rem/yr	15 TO 20% OF MPD FOR RADIATION WORKERS
PASSENGERS: GROSS INDIVIDUALS (WITH EVASIONS, FEB. 1956)	NEGLIGIBLE < 0.45 rem/yr	< 90% OF MPD FOR POPULATION, ONE TIME IN 10 yr

DOSE EQUIVALENTS FOR SST OCCUPANTS

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