AN EXPERIMENTAL MEASUREMENT OF GALACTIC COSMIC RADIATION DOSE IN CONVENTIONAL AIRCRAFT BETWEEN SAN FRANCISCO AND LONDON COMPARED TO THEORETICAL VALUES FOR CONVENTIONAL AND SUPERSONIC AIRCRAFT

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ABSTRACT

By utilizing beta-gamma and NTA photographic emulsions and thermoluminescent dosimeters, measurements of radiation dose have been made in conventional jet aircraft between San Francisco and London. These direct measurements are in fair agreement with computations made using a program which takes into consideration both basic cosmic ray atmospheric physics and the focusing effect of the earth's magnetic field. These measurements also agree with those made at supersonic jet aircraft altitudes in RB-57 aircraft. It is concluded that both experiments and theory show that the doses received at conventional jet aircraft altitudes are slightly higher than those encountered in supersonic flights at much higher altitudes when the longer time of exposure at the lower altitudes is taken into consideration.

A. COSMIC RAYS

The polar route from Los Angeles* to London is significant in two respects concerning cosmic radiation. First, it is a relatively long flight (about 12 hours) giving it greater time at latitude, and secondly, its flight path goes to very high magnetic latitudes.

Incoming cosmic rays are deflected away by the horizontal component of the earth's magnetic field. Thus, all energies of cosmic rays can hit the top of the atmosphere over the magnetic poles, but only high energy particles can hit the top of the atmosphere over the equator. This so-called "latitude effect" caused by the shape of the earth's magnetic field is shown in Fig. 1. The result is that the latitudes least affected by the earth's magnetic field are those above 50°. For this reason concern about radiation levels is centered on those flights which take a polar flight path. The San Francisco to London route is one of these.

There are essentially two types of cosmic radiation which are encountered by commercial aircraft: galactic cosmic rays and solar cosmic rays. (Several good reviews of these are available, Peters,[1] Waddington,[2] and a complete treatment of space physics, LeGalley and Rosen.[3])

*Although the airmail letters carrying the dosimeters were sent from Berkeley, California to Hammersmith, U.K., the vast majority of the accumulated dose was received between Los Angeles and Heathrow Airports, since all San Francisco to London planes go through Los Angeles on both east and west bound flights.

1. Galactic Cosmic Radiation

Under normal conditions the largest fraction of ionizing radiation in the altitudes used by transport aircraft (30,000-80,000 feet) is due to the secondary radiation produced when galactic cosmic rays strike the upper layers of the atmosphere. These galactic cosmic rays originate in not completely understood processes from various sources in the galaxy. Recent experiments with satellites and high altitude probes have substantiated this theory. The energy density of the galactic primary cosmic rays in free space is of the order of one electron volt per cubic centimeter. This is comparable to the energy density of starlight, the energy contained in the galactic magnetic fields, and the energy due to turbulence throughout the galaxy. Galactic cosmic ray particles have energies that are too high to be contained in our solar system and they must therefore be generated by a source outside our solar system.[4]

When these galactic cosmic ray particles reach the earth's orbit, four processes have already occurred: (1) "initial acceleration followed by diffusion through the galaxy;" (2) "possible post acceleration;" (3) "modulation by the solar wind;" (4) "momentum selection by the solar magnetic field."[4] The galactic cosmic rays produce secondary radiation in the upper atmosphere which is then encountered by commercial aircraft. These secondaries produce the major biological dose received by passengers and crews. The atmospheric secondaries are conveniently described in the following categories: (1) chemical composition and charge composition; (2) energy distribution; (3) distribution in latitude due to the earth's magnetic field and in altitude due to the shielding provided by the air.

At the top of the atmosphere the particle flux due to cosmic rays is about 85 percent protons, 13.5 percent alpha particles, and 1.5 percent heavier nuclei. The entire atmosphere from sea level to outer space is a shield of 1031 g/cm^2. The primary flux is attenuated rapidly by this shield, and at an altitude of 65,000 feet, or a shielding thickness measuring from the outside in of 60 g/cm^2, 50 percent of the original protons, 25 percent of the original alphas, and 3 percent or less of the original heavier nucleons still remain uncollided, as seen in Fig. 2. The total ionization level at 65,000 feet is larger than at the top of the atmosphere due to the buildup of secondaries from collisions of the primary cosmic rays with the oxygen and nitrogen nuclei of the air.[5] This effect is illustrated by Fig. 3.[6]

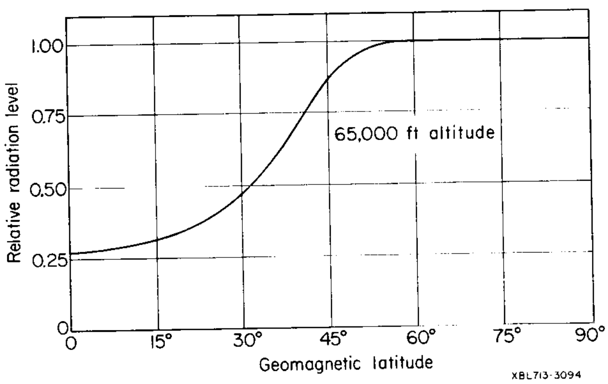

Fig. 1. Latitude dependence of galactic radiation level in the lower stratosphere showing the relative radiation level at 65,000 feet. (From Schaefer.)[5]

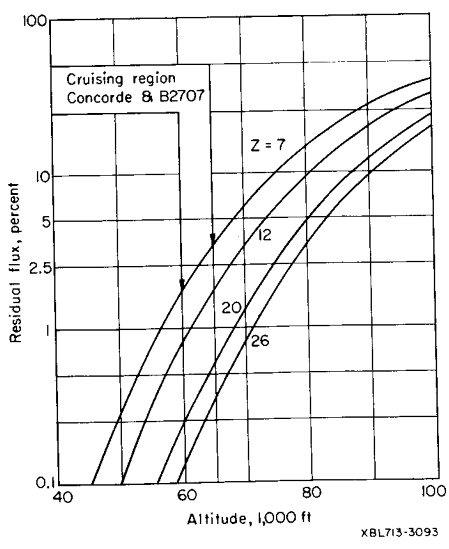

Fig. 2. The depth of penetration of heavy primaries into the atmosphere showing the residual flux versus altitude.

The heavy ions (Z > 2) left at these altitudes are not present in large numbers. Experiments with a high energy (> 10 MeV/atomic mass unit [AMU]) heavy ion particle accelerator should be conducted in order to answer the question of their biological significance. The neutrons are produced by nuclear collisions in the atmosphere. The energy spectrum of these neutrons in the atmosphere has been measured. The shape of the neutron spectrum is constant at all levels in the atmosphere below 100 g/cm^2 or 17 km, as seen in Fig. 4.[8] Near the top of the atmosphere the flux varies with solar activity by a factor of 2, and latitude by a factor of 10, as detailed in Ref. 9. The neutron flux also varies with altitude reaching a maximum at about 17 km (100 g/cm^2) (see Fig. 5). After taking into account the various measurements and calculations available, the following table seems to represent the best estimates of the galactic cosmic ray neutron flux. (See Table I.)

Table I. Galactic cosmic ray neutron flux and dose rate in relation to altitude

Altitude (feet)	Flux density: Observed at 41°N ($n/cm^2 \cdot sec$)*	Flux density: Estimated at 90°N ($n/cm^2 \cdot sec$)†	Dose rate: at 41°N (µrad/hr)‡	Dose rate: at 90°N (µrad/hr)‡
0	5.4×10^{-3}	5.9×10^{-3}	4.3×10^{-2}	4.7×10^{-2}
10,000	4.0×10^{-2}	5.0×10^{-2}	3.2×10^{-1}	4.0×10^{-1}
20,000	1.6×10^{-1}	2.4×10^{-1}	1.3	2.0
30,000	5.0×10^{-1}	7.5×10^{-1}	4.0	6.0
40,000	7.9×10^{-1}	1.2	6.3	9.4
50,000	1.1	1.8	8.8	14.5
60,000	1.1	2.0	8.8	16.7
70,000	1.0	2.7	8.0	21.5
80,000	0.9	3.9	7.4	31.8

(from Patterson, et al)[10]

*Experimental data from HAYMES.[11]

†The values observed at 41°N were multiplied by factors from LINGENFELTER[9] to obtain the estimated values for 90°N latitude.

‡Values in rads were calculated with flux density-to-dose conversion factors given in Handbook 63 of the National Committee on Radiation Protection and Measurements of the U. S. National Bureau of Standards.[12]

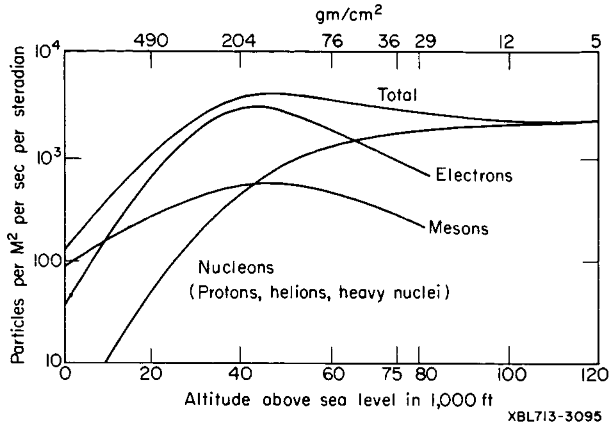

Fig. 3. Altitude profile of particle transition of cosmic ray beam in the atmosphere giving the composition at various altitudes.

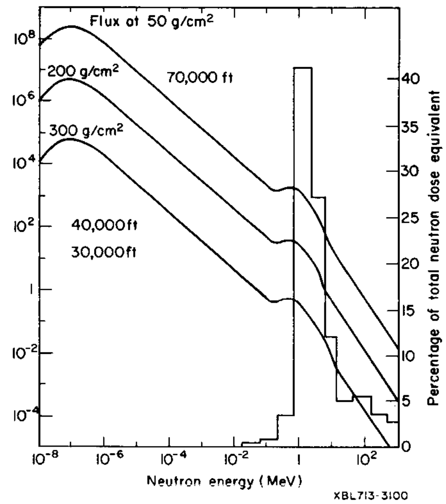

Fig. 4. Combined galactic cosmic ray neutron energy spectrum (from Patterson, et al Ref. 10) and the distribution of the dose equivalent resulting when the spectrum is multiplied by the values of RBE given in Handbook # 63 of the National Committee on Radiation Protection and Measurements of the U. S. National Bureau of Standards.[12] (from Upton, et al.)

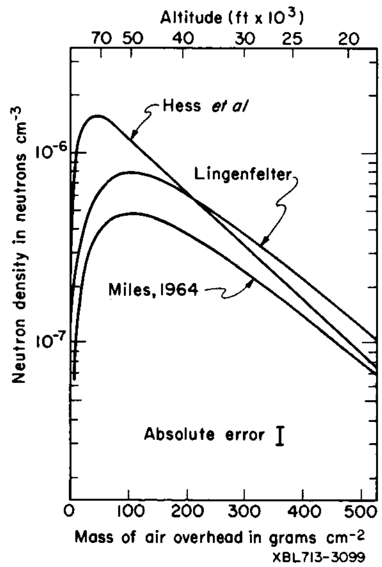

Fig. 5. Galactic cosmic ray neutron flux in relation to altitude.

2. Solar Cosmic Radiation

As previously stated, under normal conditions the solar contribution to the cosmic ray spectrum is minor compared to that of galactic origin. Occasionally, however, the sun erupts with an explosive disturbance or "solar flare" which sends large numbers of x-rays and charged particles into space. The solar flares occur with a wide range of intensities and the probability of occurence follows the 11-year cycle of solar activity fairly closely. Low-energy solar flare events, even of large magnitude, are of relatively little consequence at lower levels of the atmosphere, or at low latitudes. Concern, however, is generated by the possibility of a flare of magnitude similar to that of February 23, 1956. Figure 6, from Foelsche et al., shows the relative importance of such a large flare. The dose in rem/h at various altitudes in this flare is estimated to have been as follows:

Altitude	ft: km:	65,000 20	50,000 15	40,000 12	30,000 9
Dose equivalent in rem/h					
Upper limit:					
Feb. 1956		2.9	1.8	1.0	0.45
Lower limit:					
Feb. 1956		0.45	0.2	0.1	0.025

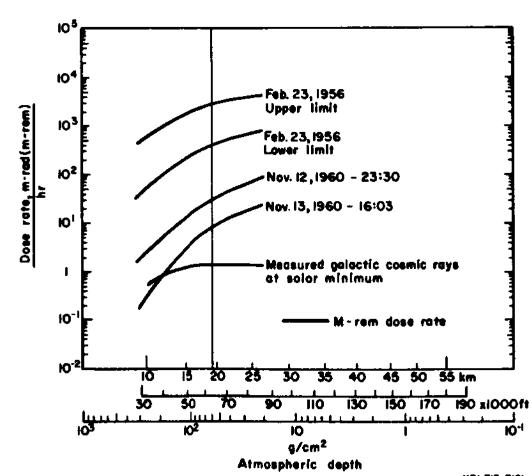

Fig. 6. Dose rates during the large solar events of February 23, 1956 (maximum phase), and November 12, 1960, at 1840, 2330, and 1603 (Nov. 13) universal time.

(from Foelsche, et. al.)[13]

Figure 6 shows dose equivalents which are higher than comparable earlier dose estimates. This calculation of greater penetration of biologically effective components is due mainly to energetic neutrons resulting from nuclear interactions of high energy primaries and secondaries. These neutrons then have a much greater probability of deep penetration, since they have no charge and are not slowed by ionization.[13] (For a detailed discussion of how these curves are derived see Ref. 13.)

C. THE EXPERIMENT

The dosimetric measurements were made by emulsions of three types sealed in plastic packets. These packets were sent by air mail back and forth from Berkeley, California to Hammersmith (London), England, until a dose sufficiently above background had accumulated. Although there were some small variations in the contents of certain packets, all were basically the same. Pieces of polyvinyl-chloride (0.6 mm thick) were cut to the size of a regular business envelope (10 cm × 23 cm). The packet was compartmentized and sealed with a radio-frequency plastic welder. Each packet contained β-γ films, NTA films, one 600μ emulsion, and occasionally CaF_2 thermal luminescent detectors (TLD). Before sealing, the entire packet was flushed with dry nitrogen gas to reduce photographic fading of the latent image by decreasing the relative humidity and decreasing the atmospheric oxygen in contact with the emulsion.[15]

Each packet contained four β-γ films. Two of these films were unexposed, the third film was pre-exposed to 20 mr, and the fourth film was pre-exposed to 100 mr of radium x-rays. One NTA film was pre-exposed to 20 mrem and the other to 100 mrem of PuBe neutrons.

From a schedule obtained from the post office and considering the number of available flights, it is reasonable to assume that at least 80% of the packets made the trip by the polar route, rather than landing in New York. Polar flights from San Francisco to London always go via Los Angeles on a flight profile approximately like that seen in Fig. 7. They usually go over the southern part of Hudson Bay, Baffin Island, and the southern third of Greenland. Each flight is flown over the predicted "least time" route based on the latest weather predictions. Some flights may be considerably south of Greenland, occasionally as far south as Atlanta, although this is rare. These variations probably don't affect the galactic cosmic ray dose since they take longer at a lower dose rate, which has a compensating effect on the integrated dose. The solar flare dose, if any, would be reduced by a larger factor by the lower magnetic latitude. Since few flares occurred during this experiment, these relatively rare and self-compensating route variations have little effect on our results.

Calculations made at Boeing Aircraft Co. indicate that one should expect about 5 mr/round trip.[16] Since the lower limit of sensitivity for the film is around 10 mr, each packet was sent on about five round trips. Unfortunately, there were no large flares and only one small flare during the experiment. Three groups of packets completed five round trips.

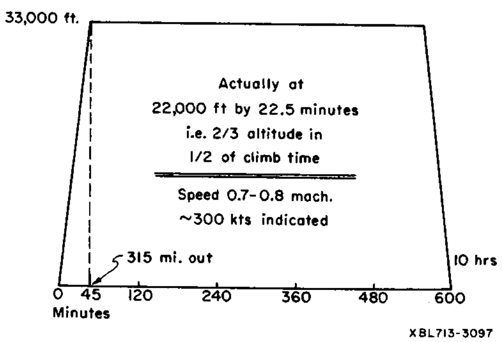

Fig. 7. Flight profile of a typical flight between Los Angeles and London from TWA.

D. BACKGROUND RADIATION

Realizing that from the time the film is sealed until it is developed, it spends more time at sea level than at altitude, it is necessary to estimate the dose of ionizing radiation which is accumulated during the time not spent in the aircraft. Approximately 3 mr were accumulated by each film when it was not at flying altitude.

E. ANALYSIS OF β-γ FILM DATA

In interpreting the data there were two experimental factors which needed special mention. First, these films, all from the same emulsion number, were packaged, exposed, and developed in three different groups; and secondly, the time which elapsed from loading to development in the three different groups was different, even though the time which each group spent in the air was essentially the same. The total dose gathered on these films represents about 2052 hours of exposure at altitudes as calculated from the flight profile in Fig. 7.

The average additional dose from cosmic rays of all flights from December, 1969, to July, 1970, was 12.5 ± 4 mr/round trip with a lower limit of 8.3 mr/trip and an upper limit of 16.1 mr/round trip.

The experience which has been gained over many years in reading this type of film indicates that the data is reasonable. It may not be possible to attach dosimetric significance to the measurements of any one film, but, in view of the large total number of hours which the film spent in the air, the average is probably significant.

Although no large solar flares occurred during the experiment, an attempt was made to correlate enhanced solar activity with those packets which showed a higher dose. This was only mildly successful.

F. THE TLD's[18, 19]

The TLD's (thermoluminescent dosimeters) were CaF_2. Each reading is actually an average of three dosimeters contained in a small plastic disk. All reading and calibrating of these dosimeters was done at the Lawrence Radiation Laboratory, Livermore, under the direction of D. E. Jones and R. E. McMillan, of the Hazards Control Group.

Due to their greater sensitivity (down to 0.1 mrad) TLD dosimeters were sent on only one round trip before being read. Of special interest is the TLD sent on the 30th of May. It was in the air when the first proton event in 45 days occurred. Unfortunately, on this particular day a TLD was not sent via JFK and so no comparison could be made between the polar and lower magnetic latitude routes. However, the measurement during the flare was clearly above the other measurements.

A description of the flare of May 30, as given by ESSA, is as follows:

> "The proton event was associated with an imp IN* in Class M flare at 30/0240 Z, again in region 760. The 1-8A x-ray burst associated with this flare had a peak flux of only 0.04 erg per sq cm per cm per sec but a total duration of 6 hours. Protons were first detected by the ATS-1 satellite at about 30/0800 Z and were of the order of 350 and 16 particles per sq cm per sec in the 5 - 21 and 21 - 70 MeV channels respectively. Associated riometer absorption at 30 MHz was 1 Db or less."

What is the meaning of the dose during the flare, compared to average conditions? If the readings for the four previous days from the polar route are averaged together using the amounts over the 4.0 mrad background one gets an average of 1.925 mrad/round trip. We assume that half of this dose was accumulated during each flight direction or that on a no-flare trip the extra amount of radiation from flying is about 1 mrad. There was an increase of about 50% per round trip due to the flare.

G. THE BOEING CALCULATIONS

The Boeing calculations[16] were made by a code originally programmed by Stanley Curtis (now at Lawrence Radiation Laboratory, Berkeley, California), which gives tissue doses due to galactic cosmic radiation during subsonic and supersonic flight for times of minimum solar activity and average solar activity. The results of the twelve city pairs, which were chosen for analysis, are shown in Table II for minimum solar and in Table III for average solar conditions.

Table. II. Results of Boeing's calculations for dose in mrem obtained when flying between various city pairs for solar minimum conditions.

City Pair	Block time* (BT) -hrs-	mrad/BT-h	mrad/round trip	mrad/600 BT-h
	Subsonic Flight-35000			
Paris-Anchorage	9.45	0.240	4.54	144
Los Angeles-Paris	11.15	0.239	5.33	144
Anchorage-Hamburg	8.95	0.239	4.27	143
Chicago-Paris	8.35	0.237	3.96	142
New York-Paris	7.45	0.234	3.48	140
Montreal-Paris	7.05	0.232	3.27	139
New York-London	7.05	0.232	3.27	139
San Francisco-N. Y.	5.45	0.210	2.29	126
Los Angeles-N. Y.	5.25	0.201	2.11	121
Los Angeles-Washington	4.95	0.195	1.93	117
Los Angeles-Chicago	3.95	0.186	1.47	112
Sydney-Acapulco**	17.45	0.131	4.57	79
	Supersonic Flight 60-64000			
City Pair	Block time (BT) -hrs-	mrad/BT-h	mrad/round trip	mrad/600 BT-h
Paris-Anchorage	3.25	0.608	3.95	365
Los Angeles-Paris	3.85	0.594	4.57	356
Anchorage-Hamburg	3.05	0.594	3.62	356
Chicago-Paris	2.85	0.574	3.27	344
New York-Paris	2.65	0.553	2.93	332
Montreal-Paris	2.45	0.546	2.67	328
New York-London	2.45	0.545	2.67	327
San Francisco-N. Y.	2.05	0.422	1.73	253
Los Angeles-N. Y.	1.95	0.390	1.52	234
Los Angeles-Washington	1.85	0.368	1.36	221
Los Angeles-Chicago	1.55	0.338	1.05	202
Sydney-Acapulco**	6.25	0.173	2.16	104

* Time in the air ** Two stopovers SOLAR MINIMUM CONDITIONS

*IN - A size and intensity evaluation. In this case area 2.1 - 5.1 sq deg with normal intensity.

Table III. Results of Boeing's calculations for dose in mrem obtained when flying between various city pairs for solar average conditions.

City Pair	Block time* (BT) -hrs-	mrad/BT-h	mrad/round trip	mrad/600 BT-h
Subsonic Flight-35 000				
Paris-Anchorage	9.45	0.215	4.07	129
Los Angeles-Paris	11.15	0.215	4.79	129
Anchorage-Hamburg	8.95	0.214	3.84	129
Chicago-Paris	8.35	0.213	3.56	128
New York-Paris	7.45	0.210	3.13	126
Montreal-Paris	7.05	0.209	2.94	125
New York-London	7.05	0.209	2.94	125
San Francisco-N. Y.	5.45	0.190	2.07	114
Los Angeles-N. Y.	5.25	0.183	1.92	110
Los Angeles-Washington	4.95	0.177	1.75	106
Los Angeles-Chicago	3.95	0.169	1.34	102
Sydney-Acapulco**	17.45	0.126	4.40	76
Supersonic Flight 60-65 000				
City Pair	Block time* (BT) -hrs-	mrad/BT-h	mrad/round trip	mrad/BT-h
Paris-Anchorage	3.25	0.486	3.16	292
Los Angeles-Paris	3.85	0.481	3.70	289
Anchorage-Hamburg	3.05	0.478	2.92	287
Chicago-Paris	2.85	0.464	2.64	278
New York-Paris	2.65	0.449	2.38	269
Montreal-Paris	2.45	0.443	2.17	266
New York-London	2.45	0.442	2.17	266
San Francisco-N. Y.	2.05	0.351	1.44	211
Los Angeles-N. Y.	1.95	0.329	1.28	197
Los Angeles-Washington	1.85	0.313	1.16	187
Los Angeles-Chicago	1.55	0.288	0.89	173
Sydney-Acapulco**	6.25	0.166	2.08	99

*Time in the air ** Two stopovers SOLAR AVERAGE CONDITIONS

In this calculation the computer utilizes geographical coordinates of the cities, altitude-distance flight profiles and block times. The program then changes these to geomagnetic latitudes and longitudes and pressure altitude as it follows the aircraft on a great circle route. At 0.1 hour intervals, the ionization density (ion pairs per cm^3 per sec per atm of air) is converted to an equivalent tissue dose rate in mrads per hour with all the appropriate conditions taken into account. The dose rate is then integrated and accumulated over the entire flight.

In particular, note that the direct Los Angeles - Paris flight is 5.33 mrad/round trip and that the same trip made by way of New York is 5.59 mrad/round trip. In general, while more southerly routes have a lower hourly dose rate, due to the larger area of the earth in the equatorial and temperate zones, the flight routes are longer and more time is spent in these lower dose rate regions. Thus, there is a compensating effect which tends to make doses on polar flights almost the same as those on lower latitude flights. There is a similar compensating effect of altitude. Subsonic flight at 35,000 ft takes about 3 times as long as supersonic flight over the same route at 65,000 ft. Since the dose rate is about 3 times higher at 65,000 ft relative to 35,000 ft these effects cancel. In fact the doses in the subsonic 35,000 ft flights are about 20% higher than in the supersonic range, and are undoubtedly given to far more people.

J. MEASURED COSMIC RAY NEUTRON SPECTRUM

One of the 600 μ emulsions was scanned for proton recoils, and these in turn converted to the neutron spectrum in Fig. 8.

The emulsions were read using the random-walk method described by Lehman. Using this method, 1150 proton recoil tracks were measured in the emulsion, which is approximately 2 cm × 2 cm × 600μ in size. This data is then introduced into a computer program which determines the track-length energy. The number of tracks per energy interval DN/P*DE is then plotted versus energy. (See Fig. 8.) The error bars are also determined in the program. From this a smooth proton spectrum is drawn.

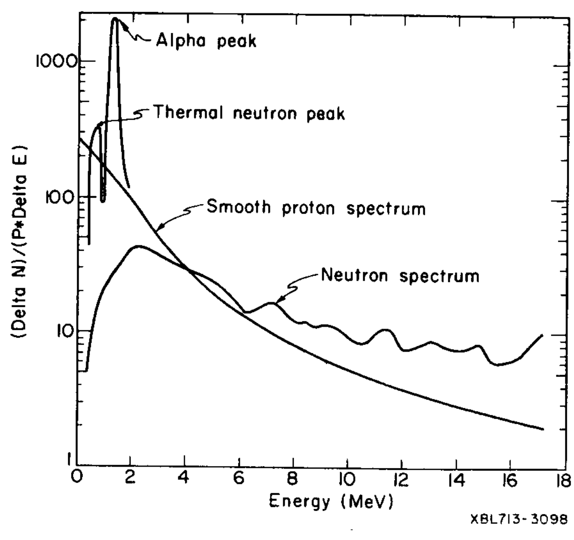

Figure. 8. Cosmic Ray neutron spectrum obtained by measuring proton recoil track lengths in the 600 micron emulsion 1150 tracks were scanned in obtaing this spectrum.

The two peaks at the low end of the proton spectrum are produced systematic effects. They are caused by nitrogen in the emulsion (an $[n_{th}, p]$ reaction) and alphas from thorium and radium impurities.

Points from the smooth proton spectrum are then introduced into another program which determines the neutron spectrum. (See Fig. 8.) A second plot of this neutron spectrum was made with a linear scale. (See Fig. 9.) Then using the expressions in Table IV[20] an integral rem dose was calculated for each energy interval. This rem spectrum was then plotted with the linear neutron spectrum for comparison. (See Fig. 9.)

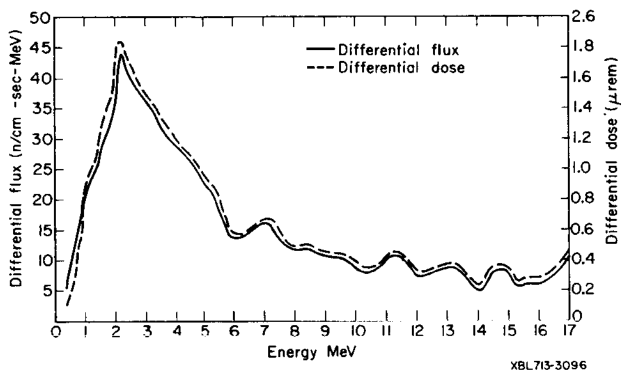

Figure 9. Comparison of Energy Spectra

K. CONCLUSIONS

The average of the experimental measurements was:

β-γ film	12.5 mr/rd trip average
TLD's	2.0 mrad/rd trip average
Boeing calculations	5.5 mrad/rd trip average

One reason for the larger β-γ film reading is that the film has a wider response to a wider γ spectrum than the TLD. This is especially true in the low energy end of the spectrum. Also, the background correction subtracted from each dosimeter is a different percentage of the total reading in each case. The β-γ film dose represents all radiation received from cosmic rays and radioactive x-ray background while on the ground, as well as while in the air. The TLD dose represents only what is gained in the air since the controls were not kept in our low level cave, but themselves received the full sea level cosmic ray and background γ exposures. The Boeing calculations represent the dose obtained from cosmic rays only while flying.

If the same background correction of 4 mrad used for the TLD's is subtracted from the β-γ film, then the average cosmic ray dose for the film is lowered to about 8.5 mr. This would then be in good agreement with the calculation. The question to resolve is whether the dosimeter or the calculation is more accurate. The strongest tendency is to place more faith in the TLD's. First, they show very consistent readings at about 10% of the minimum measurable dose of the films and judging from their response to the one solar flare which they encountered, their response seems to be internally consistent. Secondly, they were under much closer control than the film, since they made only one round trip. The film spent many weeks being exposed and perhaps fading. The chance of encountering some unexpected phenomenon on one trip is much less likely with the TLD than it is with the films which made five trips.

Table IV. Analytic expressions for dose equivalent vs neutron energy

Energy range (MeV)	$n\text{-cm}^{-2}\text{-sec}^{-1}$ equivalent to $1\ \text{mrem-h}^{-1}$
$< 10^{-2}$	232
$10^{-2} - 10^{0}$	$7.20\ E^{-3/4}$
$10^{0} - 10^{1}$	7.20
$> 10^{1}$	$12.8\ E^{-1/4}$

This experiment indicates that further work should emphasize the use of the TLD's. The Boeing calculations are probably quite realistic. The total dose on 35,000 subsonic flights is about 20% higher than on 65,000 ft supersonic flights.

The neutron dose also requires further consideration. Making the measurement over the shortest possible time period seems to be the key to this problem. At the same time as the measurement is being made a careful check on the amount of fading taking place during the measurement must be made.

A more complete description of this experiment can be found in UCRL-20052, A Measurement of Cosmic Radiation Dose: Jet Aircraft Polar Route San Francisco to London, by Michael F. Boyer (M.S. Thesis, 1970).[22]

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