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NAVAL AEROSPACE MEDICAL INSTITUTE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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RADIATION MEASUREMENTS AT SUPERSONIC TRANSPORT ALTITUDE WITH BALLOON-BORNE NUCLEAR EMULSIONS*

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Bureau of Medicine and Surgery
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SUMMARY PAGE

THE PROBLEM

While reliable data on the total ionization dosage of galactic radiation at SST altitude are available, the particle make-up and energy distribution of the flux producing that dosage has not been analyzed well enough to allow an accurate assessment of the dose equivalent that would be produced in a human target. It is particularly the flux components with a high LET, mainly neutron recoils and low energy protons of other origin, on which existing information is incomplete. Since these components enter the assessment of the dose equivalent with QF values up to 10, they have to be determined very accurately and with good LET resolution with instruments of tissue equivalent response.

FINDINGS

On a balloon flight out of Fort Churchill, Canada which floated at 65,000 feet for 19 hours during solar maximum at a Quiet Sun (22 August 1968), radiation packs were flown, and each contained a single K.2 nuclear emulsion sheet embedded in tissue equivalent moderating material. Because of its low sensitivity, the K.2 emulsion recorded only the proton flux from zero to 20 Mev, yet with excellent LET resolution. Track and grain count analysis furnished an absorbed dose rate of 0.17 millirad/hour and a dose equivalent rate of 0.49 millirem/hour. The grain count indicated that as much as 50 per cent of the dose equivalent is due to protons of less than 0.9 Mev. Presumably, the bulk of these low energy protons are neutron recoils. The results emphasize that accurate measurement of the galactic dose equivalent at SST altitude requires instrumentation with high resolution of the LET closely up to the Bragg peak of protons and responding to particles of a few micra residual range in tissue.

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INTRODUCTION

The prospect of large-scale passenger operations with Supersonic Transport (SST) flying in the altitude region of 65,000 feet has raised the question of possible effects on crew members and passengers from a radiation environment substantially different from sea level. Main attention usually is focussed on solar protons from large flare events. However, even liberal upper-limit estimates indicate that, as far as the accumulated exposure to the population over long time spans is concerned, the ever-present galactic radiation level is by far a larger contributor than the rather infrequent giant flare events which would penetrate the atmosphere deeply enough to increase the radiation level at SST altitude. Moreover, it would require quite a coincidence of adverse circumstances for an SST to stay unaware of a large flare event in progress and not take evasive action. It is seen then that the galactic radiation exposure should be the main point of concern.

In an earlier report (1), a critical survey was conducted on the available information on galactic radiation levels throughout the Earth's atmosphere with special emphasis on the altitude region about 65,000 feet. It was found that, while detailed and accurate data exist on the total ionization dosage, a reliable assessment of the dose equivalent in a human target at SST altitude encounters difficulties due to the lack of sufficient information on the share of the neutron component in the total ionization in particular and of low energy secondary protons in general. Since the just-named flux components produce their absorbed dose in tissue at a high Linear Energy Transfer (LET), QF values substantially greater than 1.0 for establishing the dose equivalents have to be applied. This creates quite some changes in the order of importance of the various flux components as the physicist sees them. Obviously, if a component that contributes to the absorbed dose only a few per cent has an LET spectrum that calls for a QF = 10, a larger error in its determination would seriously affect the total dose equivalent.

The following report presents and discusses the results of measurements with balloon-borne nuclear emulsion packs at SST altitude. The experimental design was such that the track population in the emulsion reflected directly the flux of low energy protons in the tissue equivalent (TE) material surrounding the emulsion on all sides. The investigation was carried out under contract with Langley Research Center, NASA. The radiation packs accompanied a main payload consisting of neutron spectrometer equipment. Packs were flown on a number of flights, each of them sampling a different altitude. One flight, launched on 22 August 1968 out of Fort Churchill, Canada, maintained a level altitude of 65,000 feet for 19 hours. It is the data of this particular flight that are presented below. No solar activity was recorded during the entire flight time; therefore, the data are representative of galactic radiation at solar maximum for a Quiet Sun.

METHOD OF MEASUREMENT

Nuclear emulsion, although in itself not at all a TE material, can be used as a TE radiation sensor for radiations of sufficiently high penetration if a single thin layer is embedded in TE material. In such a system, the flux and energy distribution prevailing in the embedding material is not significantly altered by the thin layer of foreign material. Therefore, the track population recorded in the emulsion layer is representative of the population in the TE material itself.

The standard radiation packs used in our experiments consisted of a single layer of Ilford K.2 emulsion of 100-micra thickness on a Melinex base of 180 micra. The emulsion sheet was sandwiched between two lucite layers of 1-mm thickness each and the sandwich placed between two wooden blocks of 1.5 x 1.5 x 1.5 inch size. The entire unit was tightly wrapped in Mylar plastic and sealed with Electric Tape.

The low sensitivity of the K.2 emulsion furnishes good grain resolution almost down to the end, i.e., to zero energy of a proton track. The price to be paid is the limitation of recognizeable proton tracks to the energy interval from zero to about 25 Mev, depending on the degree of development. Within the frame of the present investigation where interest is focussed on the high LET component of the local flux, the limitation in question is of no disadvantage inasmuch as the energy interval to 25 Mev well exceeds the region within which elevated QF values have to be used. In fact, the substantially lower background of the K.2 resulting from its low sensitivity facilitates scanning procedures considerably.

The determination of LET distribution and energy spectrum of a proton population in nuclear emulsion is a well-established routine (2). With the aid of a long proton "ender," the grain-density/range function is recorded. From the known LET/range function for emulsion, grain density can be converted directly to LET. Equally easy would be the step from range to energy since the energy/range function for emulsion is also well known. However, for measuring absorbed doses and dose equivalents, data evaluation in terms of LET is greatly preferable since the LET directly denotes absorbed energy.

As mentioned above, the determination of tissue dosages by means of the track and grain count in emulsion rests on the proposition that all tracks that enter the emulsion from the outside originate in the TE material surrounding the emulsion on both sides. Certain limitations to that proposition for low energy protons entering the emulsion at a grazing angle have been discussed in detail in an earlier report (l.c., 2). These limitations are due to the short range of the low energy protons and make themselves felt as the so-called instrument cutoff also in most other measuring devices. Since it is exactly the low energy protons which require QF values above 1.0, the instrument deficiency in question is of special importance in the assessment of dose equivalents. It is the specific objective of the present investigation to furnish quantitative data on this particular aspect of the radiation exposure at SST altitudes.

RESULTS

Figure 1* shows the grain count/range function for the flown K.2 emulsion obtained as the mean of three long "enders." It is seen that the K.2 emulsion affords indeed a very satisfactory grain count resolution down to the near-end of the track. Merely at the very end where the LET approaches the Bragg peak in the last few micra of residual range, the LET increases so precipitously that the grain count becomes statistically meaningless. Therefore, the intercept of the curve in Figure 1 with the ordinate at zero range remains undetermined. For this reason, the grain count/range and hence the grain count/LET relationship has been used, in the present investigation, only down to a residual range of 50 micra emulsion, corresponding to a grain count of 140 gr/100 micra Em which in turn corresponds to a kinetic energy of 2.3 Mev and an LET of 15.3 kev/micra T.

In the actual scan a total of 573 track segments in an area of 6.3 mm^2 of the K.2 emulsion was analyzed by determining grain count and length of each segment. Table I is based on the uncorrected raw scores with track segments ordered in grain classes and the combined length of the track segments in each class expressed in terms of the equivalent unidirectional flux; this means that the combined length has been divided by the scanned emulsion volume. As shown in earlier emulsion monitoring on Project Mercury (3), the equivalent unidirectional flux would produce the same energy dissipation in the scanned emulsion volume as would the actual multidirectional flux.

By establishing the cumulative sum of the fractional fluxes in consecutive classes, one obtains the integral LET spectrum shown in Column 5 of Table I and in Figure 2. Using for further evaluation the smooth curve of best fit drawn in Figure 2, one can establish new LET classes of equal logarithmic width as shown in Column 1 of Table II. Reading the integral flux values for the interval limits from the smooth curve in Figure 2 and taking their differences furnishes the fractional fluxes shown in Column 3. The product of the fractional flux and the mean LET in each interval represents the absorbed energy (Column 4) which can be expressed in terms of millirad (Column 5). It is seen that a sizeable dose fraction is contributed by the highest LET class. That class contains all protons with an LET equal to or greater than 250 Mev/(g/cm^{2}T), corresponding to an upper energy limit of 0.9 Mev. In other words, a sizeable fraction of the absorbed dose is produced by particles of rather low energy. It is evident that, in a heavy vehicle of 175 tons with a very complex shield distribution such as the Concorde, this dose contribution would be subjected to large variations, depending on the particular location within the vehicle. The full meaning of this finding for the problem of adequate dosimetry at SST altitude becomes apparent when we proceed from absorbed doses to

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*In order not to break the continuity of the text, all tables and illustrations appear at the end.

dose equivalents. For this purpose, the dose fractions in Column 5 of Table II have to be multiplied by QF values based on their individual LET values.

In its latest publication (4), the International Commission on Radiation Protection (ICRP) recommends a QF/LET relationship set forth in a table listing only selected values. In the present analysis, QF values were interpolated graphically with the aid of a curve of best fit through the points of the official tabulation of the ICRP. Table III lists the resulting QF/LET function together with the corresponding values of energy and range in tissue for protons. The interpolated QF values are shown in Column 6 of Table II. Multiplied by the absorbed dose fractions in Column 5, they furnish the dose equivalents in Column 7. It is seen that the total dose equivalent is 2.6 times larger than the total absorbed dose and that this increase is due mainly to the large contribution to the dose equivalent in the highest LET class which accounts for 40 per cent of the total dose equivalent.

Most significant in the foregoing analysis is the fact that, within the combined LET interval of the three highest classes, the highest class contributed by far the largest share to the dose equivalent. This circumstance would seem to call for a more detailed determination of the LET distribution within this class itself, especially since the class comprises the entire upper end of the LET scale from 250 to the Bragg peak of 850 Mev/(g/cm^{2}T). Consulting the integral LET spectrum in Figure 2, one sees that the experimental points based on the raw scores of the actual scan define only rather poorly the slope of the spectrum in the region of the highest LET class. This is due to the fact that all track segments with a grain count greater than 140 gr/100 micra Em had to be lumped into one class and thus remain unresolved with regard to the precise values of their individual LET's. In order to avoid overemphasis of the dose contribution of this class, the smooth curve of best fit in the upper right-hand part of the curve of Figure 2 was drawn with a conservatively low slope. This is evident from the fact that the curve passes above the points at log LET = 1.03 and 1.18. Direct intersection of these points would have furnished larger differential fluxes in the last three classes at the upper end of the LET scale in Table II.

Aside from the just-mentioned slight underrating of the dose contributions in the three highest classes, an additional problem arises for the highest LET class. Since this class contains the Bragg peak, i.e., the steep maximum of the LET of 850 Mev/(g/cm^{2}T) with an ensuing even steeper drop to zero, a representative mean LET for computing the absorbed dose cannot easily be established. The conservatively low value of 350 Mev/(g/cm^{2}T) shown in Table II is essentially an arbitrary choice. A more accurate assessment of the LET distribution in the highest LET class could be made by assuming that the fractional flux of 75 protons/cm^2 in that class is evenly distributed over all energies in the interval. This approach is shown in Table IV. It is seen that it brings out well the precipitous increase of the LET in the Bragg peak in the two energy classes from 0.3 to 0.2 and from 0.2 to 0.1 Mev. As seen from the total of Column 5 and that of Column 7 of that table, this spectral model furnishes an absorbed dose of 0.593 millirad and a dose equivalent of 5.676 millirem, values that markedly exceed the coarse estimates in Table II.

Still another model for the LET distribution in the highest LET class can be based on the assumption of an even spread of the flux over all ranges. This model is presented in Table V. It is seen that it furnishes, for absorbed dose and dose equivalent, values between those of the estimates in Table II and the linear energy model in Table IV.

There are no specific experimental or theoretical clues available that could aid in the decision which of the two distribution models should be given preference. Two basically different kinds of low energy protons enter the emulsion from the tissue equivalent material, neutron recoil protons and secondary protons from nuclear interactions. From the nature of the mechanisms involved, neither type is likely to exhibit sharp resonance peaks at particular energies or residual ranges. Therefore, the resulting energy or range distributions can be expected to be smooth continua although not necessarily showing complete equipartition in energy or range as assumed in the two proposed models. Nevertheless, the mean of the three approaches presented above would seem acceptable as a first approximation, especially since the uncertainty in question concerns only one of nine classes that make up the total dose. The three individual values and their mean are shown in Table VI. For the conversion of total doses to dose rates, remember that the total time at altitude was 19 hours.

The real importance of the analysis of the dose contribution from the highest LET class does not rest on its particular numerical value but on the fact that the various spectral models agree very well in the values for the absorbed dose, yet differ substantially in the dose equivalents. This finding demonstrates that a dosimeter for the radiation exposure at SST altitude should offer good LET resolution down to proton energy levels close to the Bragg peak and correspond to ranges in tissue of a few micra. Since at the same time components of high and very high penetrating power also contribute to the total dose, the construction of a dosimeter with a balanced tissue equivalent response to such an extremely heterogeneous spectrum poses quite a challenge for the instrument designer.

DISCUSSION OF RESULTS

If we attempt to interpret the results reported above in the general perspective of the radiation exposure at SST altitude, we must remember that our recordings pertain only to the proton flux in the zero to 20 Mev energy interval. Although this interval comprises all components to which QF values above 1.0 would have to be applied, it certainly does not account for the total absorbed dose. Accurate information on this total dose is not very abundant. Most recent unpublished data (5) indicate a radiation level of about 1 millirem/hour at 65,000-feet altitude recorded at a Quiet Sun during late summer 1968. That means these data hold essentially for the same radiation environment encountered in the flight of the present investigation. It is seen then that, in terms of absorbed dose, the flux of protons in the zero to 20 Mev energy band defrays somewhat less than 50 per cent of the total dose equivalent.

A special problem in measurements of low energy protons of galactic origin always arises if the share of neutron recoils is to be assessed. In the literature on radiation hazards at SST altitude, larger discrepancies exist in the numerical values of the dose contributions from neutrons. Recently, Foelsche and co-workers (6) have reported on measurements with equipment especially designed for accurate determination of flux and energy spectrum of the neutron component. These authors found, again for conditions of solar maximum and a Quiet Sun, a radiation level of 0.48 millirad/hour corresponding to 1.07 millirem/hour at 65,000 feet.

The recordings of the present investigation do not allow any distinction of neutron recoils from protons of other origin in the track population. Nevertheless, a comparison shows that the data in Table VI and those of Foelsche are compatible, since the data in Table VI pertain only to the flux component from 20 Mev to zero and therefore should be substantially smaller than Foelsche's data pertaining to the total flux.

At this point it seems of interest to discuss briefly the general aspects of neutron measurements with nuclear emulsions. Most neutron radiation fields and especially that in the atmosphere at SST altitude contain, besides fast neutrons accounting for the bulk of the flux, also thermal neutrons. The sensitivity of nuclear emulsion for thermal neutrons is very low. As Dudley (7) has pointed out, the $N^{14}(n,p)C^{14}$ reaction, which furnishes a secondary proton of 0.62 Mev energy, is of very low efficiency because of the small nitrogen content of emulsion. For the 30-micra thick NTA emulsion in the Eastman Kodak Personal Neutron Monitoring Film Badge, an absorbed dose of 0.1 millirad from thermal neutrons produces 77 tracks/cm^2. For a size of 10^{-4} cm^2 of the microscopic visual field, that value represents a track density of 1 track per 130 visual fields. This is a track count that would completely disappear in the background of blobs from terminating electrons and other artifacts which an emulsion flown for 19 hours at SST altitude will pick up.

For the measurement of fast neutrons, one has to distinguish two basically different methods of applying nuclear emulsion. One can either use emulsion itself as the radiation sensor counting the recoil protons which the fast neutrons will release in the hydrogen content of the emulsion itself, or one can embed the emulsion in hydrogenous or tissue equivalent material and record the recoils emitted from that material into the emulsion. For the former method, the efficiency is again very low because of the small hydrogen content of emulsion; for the latter, the efficiency is 100 per cent since any recoil proton entering the emulsion will produce a track. Although the latter method was used in the present investigation, the sensitivity of the former might be explicitly quoted for completeness sake. In the same 30-micra NTA emulsion referred to above, the same absorbed dose of 0.1 millirad from fast neutrons produces 18 tracks/cm^2 or one track per 550 visual fields of 10^{-4} cm^2 individual size. This shows that the situation is even worse than for thermal neutrons, although the substantially greater lengths of the recoil tracks of fast neutrons as compared to the 6 micra tracks from the $N^{14}(n,p)C^{14}$ reaction of thermal neutrons make for a much more reliable identification in the scanning process.

With regard to the thermal neutron flux at SST altitude, it should be pointed out that the poor response of nuclear emulsion would not seem to pose any problem, neither in the interpretation of the findings of the present investigation nor in regard to the galactic neutron component in the atmosphere in general. The basic mechanism of thermalization of neutrons in the process of gradual energy degradation has been very well analyzed in all its qualitative and quantitative aspects in view of its great importance in reactor technology. Applying these relationships to the general source spectrum of galactic neutrons indicates that thermal neutrons can contribute, at the most, a few per cent to the dose equivalent from fast neutrons. Direct measurements of the thermal neutron dose at SST altitude supporting the just-named conclusion have been reported by Fuller and Clarke (8).

In conclusion, it can be stated that the radiation level of 0.49 millirem/hour at 65,000 feet measured from the emulsion recordings of the present investigation agrees well with the findings of other investigators. The special significance of the present measurement rests in the fact that it furnishes a complete record of the population of low energy protons representing the equilibrium flux developing in TE material from galactic radiation at SST altitude. Although a distinction of neutron recoil protons from protons of other origin is not possible in the emulsion method, this shortcoming appears only of minor significance in a dosimetric analysis as long as the true equilibrium state of both flux components of low energy protons is correctly recorded. Since the experimental design used in the present investigation fulfills this requirement, the results furnish the true dose equivalent in tissue and spell out the specifications with regard to LET resolution for dosimetric equipment if it is to assess the dose equivalent correctly.

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Table I

Results of Track and Grain Count Analysis of Flown K.2 Emulsion

Grain Count, gr/100 micra Em	LET in Tissue, Mev/(g/cm^{2}T)	Log LET, Upper Limit	Equiv. Flux, Protons/cm^2	Integral Flux, Pr/cm^2 $\leq$ LET
< 20	< 25.6	1.408	216	216
20-29	25.6-30.3	1.481	690	906
30-39	30.3-35.2	1.547	689	1595
40-49	35.2-40.8	1.611	303	1898
50-59	40.8-46.5	1.668	386	2284
60-69	46.5-53.0	1.724	325	2609
70-79	53.0-60.0	1.778	64	2673
80-89	60.0-67.3	1.828	194	2868
90-99	67.3-78.2	1.893	140	3008
100-119	78.2-107	2.027	68	3076
120-140	107-153	2.185	87	3163
> 140	153-850	2.929	189	3352

Table II

Evaluation of Absorbed Dose and Dose Equivalent from Smooth Curve of Best Fit in Figure 2

LET Interval, Log Mev/(g/cm^{2}T)	Mean LET, Mev/(g/cm^{2}T)	Flux, Protons/cm^2	Abs. Energy, Flux x mean LET	Abs. Dose, millirad	QF	Dose Equiv., millirem
1.4-1.5	28.4	985	27,974	0.497	1.0	0.497
1.5-1.6	35.7	740	26,418	0.469	1.0	0.469
1.6-1.7	45.0	560	25,200	0.447	1.3	0.581
1.7-1.8	56.6	370	20,942	0.372	1.6	0.595
1.8-1.9	71.3	205	14,617	0.259	2.0	0.518
1.9-2.0	89.7	105	9,419	0.167	2.4	0.401
2.0-2.2	129	115	14,835	0.263	3.15	0.828
2.2-2.4	205	60	12,300	0.218	4.5	0.981
> 2.4	~ 350	75	26,250	0.466	~ 7.2	3.355
			Total	3.158		8.225

Table III

Proton Data in High LET Region

Kinetic Energy, Mev	Range in Tissue, micra	LET, Mev/(g/cm^{2}T)	Quality Factor
0.2	3.0	780	13.0
0.3	4.4	605	11.0
0.4	6.3	475	9.2
0.6	11.5	315	6.6
0.8	18.7	263	5.6
1.2	37.3	207	4.6
1.6	58.7	193	4.3
2.0	84.6	168	3.9
3.0	166	125	3.1
4.0	270	98.5	2.6
6.0	548	70.5	2.0
8.0	921	55.4	1.6
12	1900	40.3	1.2
16	3200	31.4	1.0
20	4780	26.4	1.0

Table IV

Dose Distribution in Highest LET Class Assuming Equipartition in Energy

Energy Interval, Mev	Mean LET, Mev/(g/cm^{2}T)	Flux, Protons/cm^2	Abs. Energy, Flux x LET	Abs. Dose, millirad	QF	Dose Equiv., millirem
0.9-0.8	257	8.3	2133	0.038	5.5	0.209
0.8-0.7	260	8.3	2158	0.038	5.6	0.213
0.7-0.6	269	8.3	2232	0.040	5.8	0.232
0.6-0.5	347	8.3	2880	0.051	7.1	0.362
0.5-0.4	427	8.3	3544	0.063	8.5	0.536
0.4-0.3	540	8.3	4482	0.080	10.1	0.808
0.3-0.2	692	8.3	5744	0.102	12.0	1.224
0.2-0.1	809	8.3	6715	0.119	13.2	1.571
0.1-0	~ 420	8.3	3486	0.062	8.4	0.521
	Total	~ 75		0.593		5.676

Table V

Dose Distribution in Highest LET Class Assuming Equipartition in Range

Range Interval, micra Tissue	Mean LET, Mev/(g/cm^{2}T)	Flux, Protons/cm^2	Abs. Energy, Flux x LET	Abs. Dose, millirad	QF	Dose Equiv., millirem
22-20	255	6.8	1734	0.031	5.5	0.171
20-18	263	6.8	1788	0.032	5.6	0.179
18-16	270	6.8	1836	0.033	5.8	0.191
16-14	278	6.8	1890	0.034	5.9	0.201
14-12	295	6.8	2006	0.036	6.3	0.227
12-10	324	6.8	2203	0.039	6.8	0.265
10-8	369	6.8	2509	0.045	7.5	0.338
8-6	445	6.8	3026	0.054	8.8	0.475
6-4	572	6.8	3890	0.069	10.5	0.725
4-2	750	6.8	5100	0.091	12.6	1.147
2-0	425	6.8	2890	0.051	8.5	0.434
	Total	~75		0.515		4.353

Table VI

Effect of Unresolved LET Distribution in Highest Class on Total Dose

Model	Dose in Highest Class, millirad	millirem	Total Dose, millirad	millirem	Total Dose Rate, mrad/hr	mrem/hr
Arbitrary Estimate	0.466	3.355	3.158	8.225	0.166	0.433
Equipartition in Energy	0.593	5.676	3.285	10.546	0.173	0.555
Equipartition in Range	0.515	4.353	3.207	9.223	0.169	0.485
				Mean:	~0.17	~0.49

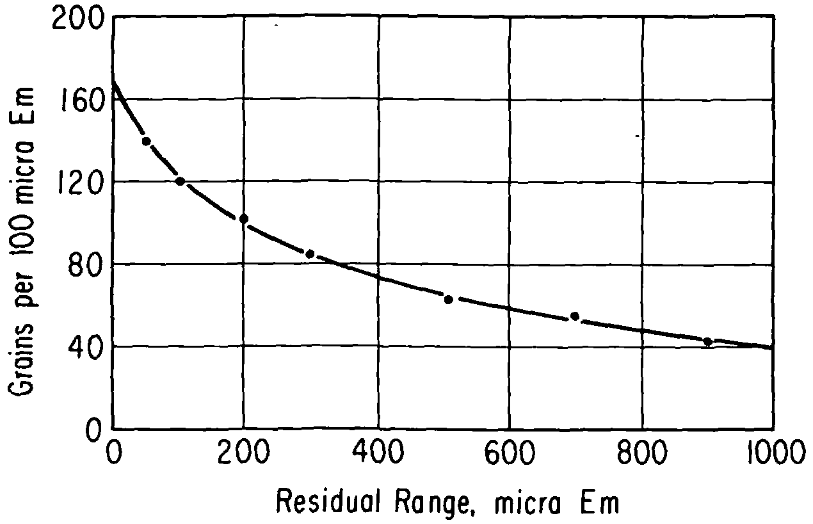

Figure 1

Grain Count/Range Function for Proton Tracks in Flown Ilford K.2 Emulsion

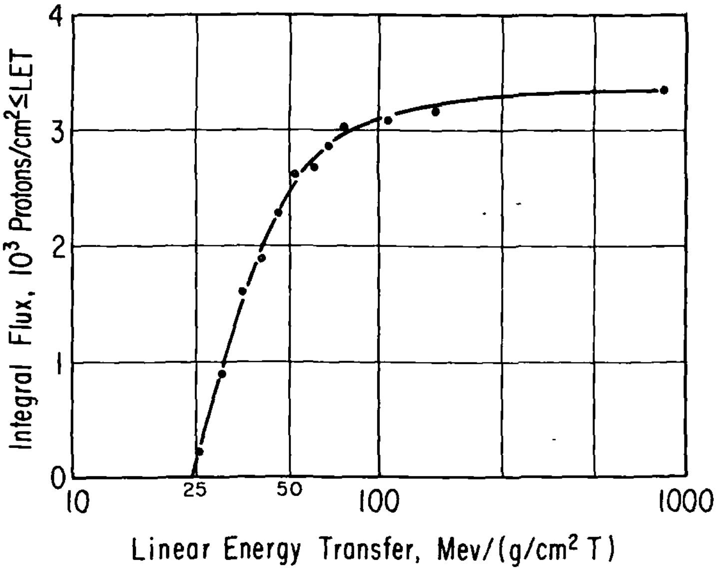

Figure 2

Integral LET Spectrum of Track Population in Flown K.2 Emulsion

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13 ABSTRACT

A radiation pack containing single Ilford K.2 emulsion sheets sandwiched between tissue equivalent material was flown on 22 August 1968 out of Fort Churchill, Canada with a balloon which floated at a level altitude of 65,000 feet for 19 hours. Conditions were those of solar maximum on a day of a Quiet Sun. Track and grain count analysis furnished an absorbed dose rate of 0.17 millirad/hour and a dose equivalent rate of 0.49 millirem/hour. According to the limited sensitivity of the K.2 emulsion, these values represent only the flux component of protons from zero to about 20 Mev. The bulk of the protons at the lower end of this energy interval appears to be made up of neutron recoils. The results indicate that dosimetric instrumentation for measuring the dose equivalent at SST altitude must possess exceptionally good LET resolution closely up to the Bragg peak of protons.

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Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Galactic radiation exposure in Supersonic Transport						
Galactic neutrons at Supersonic Transport altitude						
Nuclear emulsion as tissue equivalent radiation sensor						

DD FORM 1 NOV 65 1473 (BACK)

(PAGE 2)

Unclassified

Security Classification