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NUCLEAR EMULSION MEASUREMENTS OF THE ASTRONAUTS' RADIATION EXPOSURE ON APOLLO VII

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JOINT REPORT

NAVAL AEROSPACE MEDICAL INSTITUTE

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NUCLEAR EMULSION MEASUREMENTS OF THE ASTRONAUTS' RADIATION EXPOSURE ON APOLLO VII*

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SUMMARY PAGE

THE PROBLEM

On the 10.8-day Apollo VII mission, small packs of nuclear emulsions were carried by the astronauts on chest, thigh, and ankle. As the mission was merely preparatory to the lunar flight and remained entirely in a conventional near-Earth orbit of low inclination, it offered the unique opportunity of comparing the radiation exposure in a conventional satellite orbit with that to be encountered on later deep-space missions.

FINDINGS

A complete track and grain count analysis, carried out so far only for the radiation pack on the CSM pilot's chest, furnished a proton dose of 122 millirads. Particle spectrum and LET distribution closely resemble those found earlier on the Gemini missions. This finding is not surprising in view of the near similarity of orbital parameters from which the bulk of radiation exposure can be expected from the South Atlantic Anomaly trapped protons.

Information concerning local variations of the low energy flux that would reflect the complex directional pattern of the shield distribution is still incomplete inasmuch as the scanning effort so far has covered only about 5 per cent of the emulsion target area. However, it seems to be well established that, in marked contrast to earlier findings on Gemini VII, there are no significant differences in the numbers of enders entering the emulsions from outside and from within the astronaut's body. Presumably, this greater uniformity is a combined effect of the heavier shielding of the Apollo vehicle and of the greater freedom of movement of the crew in the larger ship, which reduce the influence of self-shielding of the body on the total shield distribution.

INTRODUCTION

The Apollo VII mission was launched on 11 October 1968 into an orbit with an initial perigee of 122.6 and an apogee of 153.5 nautical miles, a period of 89.7 minutes, and an inclination of 31.64 degrees. Apollo VII was the first manned mission and followed six unmanned missions in which the Apollo vehicle had been thoroughly tested. It completed 163 revolutions of the Earth in 260 hours.

As can be seen from the just-named orbital parameters the mission was merely preparatory to a lunar mission since it remained in a conventional near-Earth satellite orbit closely resembling that of each Gemini mission. With regard to the radiation exposure of astronauts, the Apollo VII mission thus offers the unique opportunity to establish a base line for the comparison of ordinary satellite orbits with the deep-space trajectories of later Apollo flights. Such a comparison is of very special interest since the two types of missions encounter profoundly different radiation environments. The lunar mission, on the one hand, avoids the repeated traversals of the South Atlantic Anomaly which accounted for more than 90 per cent of the radiation dose on all Gemini flights. Instead, it passes only twice and quite rapidly through more peripheral regions of the inner radiation belt. On the other hand, its trajectory lies almost completely outside the magnetosphere, and therefore the full galactic flux with no geomagnetic cutoff and, for a large part of the journey, with 4-pi incidence on the ship is encountered.

The recordings on the Gemini missions furnish such a comparative base line only to a limited extent because of the substantially lighter shielding of the smaller Gemini vehicle. The latter condition, at the same time, lends additional interest in that a comparative evaluation of the radiation exposures on Apollo VII and the Gemini missions can be made. The seventh Gemini mission appears to be of special relevance for the indicated comparison inasmuch as in its duration of 14 days, as compared to that of 10.8 days of Apollo VII, very nearly identical conditions were created with regard to the respective ratios of orbits that traversed or bypassed the South Atlantic Anomaly. The monitoring of the astronauts' radiation exposure on the Gemini missions, carried out along very similar lines as on Apollo VII, has been described in three earlier reports (1-3) and a journal publication (4) which should be referred to for a comparison of the radiation exposure with the one on Apollo VII reported below.

It must be pointed out that the present report is of a preliminary nature since, at the time it was written (January 1969), a complete track and grain count analysis was available only for one radiation pack. However, since the scanning effort had to be switched to Apollo VIII packs, it seemed desirable to write up the partial results in a finished form, making them readily available for the comparison with the forthcoming data on Apollo VIII.

TECHNIQUE OF MEASUREMENT

In view of the aforementioned fact that future Apollo missions probing into deep space will encounter a radiation field of a basically different make-up from that of Apollo VII and all Gemini missions, it seems useful to review briefly the principles and limitations of the nuclear emulsion method of determining absorbed dose. Since the radiation sensitive substance in emulsion, silver bromide, certainly is not tissue equivalent in its atomic composition, the determination of an absorbed dose in millirads by track and grain count analysis in emulsion is possible only indirectly and only for certain radiations.

If a corpuscular radiation of comparatively high penetrating power such as protons in the multimillion e-volt energy range enters a human target from all directions, a thin layer of a radiation sensitive material close to the body, and which would not noticeably alter the flux, obviously could serve as a tissue equivalent sensor if it would record correctly the number and LET of all particles traversing it. The absorbed dose in millirads produced on the body surface under the sensor could then be determined from flux and LET distribution. In fact, even the latter two magnitudes would lend themselves to a computational analysis of the depth dose distribution. For protons in particular and for a nuclear emulsion layer of 50- to 100-micra thickness, the specified condition of negligible attenuation effects on traversal is fulfilled for the energy interval from about 10 to 200 Mev. Above 200 Mev, the ratio of collision loss to ionization loss becomes increasingly larger and falsifies the primary flux by adding secondary particles. For energies below 10 Mev, the range for protons becomes so small that the shortening of residual range in the emulsion layer, especially for oblique incidence, is no longer negligible. This shortening of residual range makes itself felt in a change of the spacing of the so-called "enders," i.e., of protons reaching the end of their ionization range in the emulsion. However, this change in the spatial density of enders in emulsion as compared to tissue is governed by the stopping powers of the two media. The observed density of enders in emulsion therefore can be easily corrected before the absorbed dose in tissue is computed.

In fact, the latter method of establishing the fractional dose from enders, i.e., from protons of very low energy, is a most valuable, independent double-check of the track and grain count analysis because low energy protons produce very dense tracks for which grain counting becomes subjective and inaccurate. Quite differently, identification of a proton ender in the microscopic scanning process offers no problems.

A certain difficulty in the conversion of the enders count from emulsion to tissue arises from the fact that the ratio of the stopping powers of the two media is not constant for low and very low energies, which is precisely the energy range of interest in the present context. Focussing attention on the interval from zero to 12 Mev, which corresponds to the last 750 micra of a proton track in emulsion, we find (5) that the ratio of the stopping powers of emulsion and tissue varies from 1.7 at zero energy to 2.3 at 12 Mev, with most of the change occurring in the terminal section at very low energies. The pertinent values are compiled in Table I. It is seen, then, that for a completely accurate conversion, one would have to determine the length of each ender in the scanned emulsion volume separately and establish its corresponding length in tissue. As this procedure would slow down very severely the progress of the count, yet would furnish in return only a quite moderate gain in accuracy, we have in the data evaluation of the present investigation chosen to apply a constant mean value of 2.0 for the stopping power ratio of emulsion to tissue. This simplification seemed to be even more acceptable because of the comparatively larger unavoidable fluctuations of the enders dose resulting from the complex and highly structured shield distribution of the vehicle frame, equipment, and the astronauts' bodies themselves. This directionality of the shield distribution affects most strongly the enders since they represent the protons of lowest penetration. Furthermore, for the low dose level of only about 100 millirads encountered on Apollo VII, marked statistical fluctuations of the local enders count are superimposed on those from true changes in the shield distribution. The variations from those two effects are substantially larger than the error introduced by use of a mean stopping power ratio.

Table I

Stopping Powers of G.5 Emulsion and Muscle Tissue for Protons*

Kinetic Energy, Mev	Range in Em, micra	Stopping Power, Em	Mev/cm Muscle	Stopping Power Ratio, Em/Muscle
0.4	3.84	813.4	491.0	1.657
0.8	9.90	550.8	310.6	1.773
1.2	18.1	434.3	232.0	1.872
2	39.7	317.7	159.6	1.991
4	121	201.5	94.38	2.135
6	235	152.3	68.72	2.216
8	380	124.1	54.65	2.271
10	554	105.6	45.70	2.311
12	756	92.38	39.45	2.342

*Data by J.F. Janni (5).

RESULTS

Table II shows the numbering code of the radiation packs of the Apollo VII mission. The MSC Number holds for the finished pack as it is inserted into the receiving pouch of the astronaut's garment. The finished pack contains the emulsion pack prepared and numbered at the Naval Aerospace Medical Institute, Pensacola and the thermoluminescence dosimeter pack prepared at the Manned Spacecraft Center, Houston.

Table II

Numbering Code for Radiation Packs of Apollo VII

Position*		MSC No. PRD SN#	Emulsion Pack No.
CSM pilot	1	025	1
	2	026	2
	3	027	3
Commander	1	029	28
	2	030	6
	3	031	4
LEM pilot	1	033	9
	2	034	10
	3	035	7
Sea level controls		028	16
		032	8
		036	12

*Position code: 1, chest; 2, thigh; 3, ankle.

#Numbering system used by the Manned Spacecraft Center.

As mentioned above, at the time this report is being written only one pack (Emulsion Pack No. 1) has been subjected to a complete track and grain count analysis of the G.5 emulsion. The analysis was carried out by the method used on all Gemini missions. A proton ender of 7000 micra length served as a standard for establishing the grain count/energy function from the known range/energy function for nuclear emulsion. Grain count classes were converted to LET classes, as shown in Table III, by applying the known LET/energy functions for emulsion and tissue. By dividing the total length

Table III

Results of Track and Grain Count Analysis of G.5 Emulsion in Pack No. 1 on Apollo VII

Grain Count, gr/100 micra Em	LET in Em, kev/micron Em	LET in Tissue, Mev/(g/cm^2T)	Equiv. Flux, Protons/cm^2	Integral Flux, Pr/$cm^2 \leq$ LET
< 40	< 0.70	< 2.67	234,500	234,500
40-59	0.70-1.10	2.67-4.29	273,000	507,500
60-79	1.10-1.56	4.29-6.16	168,000	675,500
80-99	1.56-2.10	6.16-8.43	112,000	787,500
100-119	2.10-2.83	8.43-11.5	33,000	820,500
120-139	2.83-4.02	11.5-16.7	42,000	862,500
140-159	4.02-5.90	16.7-25.2	42,500	905,000
160-180	5.90-9.00	25.2-39.8	16,550	921,550
> 180	> 9.00	> 39.8	36,450	958,000

of all track segments in a class by the scanned emulsion volume, the total track length per unit volume was determined. As explained in an earlier report (6), the latter quantity can be interpreted as the equivalent unidirectional flux. This flux is listed in Column 4 of Table III.

By adding the flux values of consecutive LET classes, the integral LET spectrum can be established. Column 5 in Table III shows the pertinent values and Figure 1 the corresponding plot. The smooth curve of best fit drawn in Figure 1 was used for computing the absorbed dose. For this purpose, LET intervals of equal logarithmic width were selected as shown in Column 1 of Table IV. The corresponding LET intervals themselves and their mean values are listed in Columns 2 and 3. Column 4 lists the fractional fluxes as read from the smooth curve in Figure 1. Multiplication of these fluxes by the corresponding mean LET values furnishes the absorbed energies and absorbed doses in Columns 5 and 6.

As mentioned before, the grain count becomes inaccurate beyond about 180 grains/100 micra Em. Thus for the region beyond, no further well-defined grain count and LET classes can be set up. Rather, all track segments showing a higher grain density must be lumped together into one class for which a resolution of the LET

Table IV

Evaluation of Absorbed Dose from the Track and Grain Count Analysis of the G.5 Emulsion in Pack No. 1 on Apollo VII

LET Interval, Log Mev/(g/cm^{2}T)	Mev/(g/cm^{2}T)	Mean LET, Mev/(g/cm^{2}T)	Flux, Protons/cm^2	Absorbed Energy, Flux x Mean LET	Absorbed Dose, millirads
0.3-0.4	2.01-2.51	2.26	191,500	432,800	7.68
0.4-0.5	2.51-3.16	2.84	162,000	460,100	8.17
0.5-0.6	3.16-3.98	3.57	137,000	489,100	8.68
0.6-0.7	3.98-5.01	4.50	107,000	481,500	8.55
0.7-0.8	5.01-6.31	5.66	81,000	458,500	8.14
0.8-0.9	6.31-7.94	7.13	63,000	449,200	7.97
0.9-1.0	7.94-10.0	8.97	51,000	457,500	8.12
1.0-1.1	10.0-12.6	11.3	40,000	452,000	8.02
1.1-1.2	12.6-15.8	14.2	32,000	454,400	8.07
1.2-1.3	15.8-20.0	17.9	23,000	411,700	7.31
1.3-1.4	20.0-25.1	22.6	17,000	384,200	6.82
1.4-1.5	25.1-31.6	28.4	12,000	340,800	6.05
1.5-1.6	31.6-39.8	35.6	5,000	149,500	2.65
> 1.6	> 39.8	(39.8)	36,500	1,453,000	25.8
				Total dose:	122.0

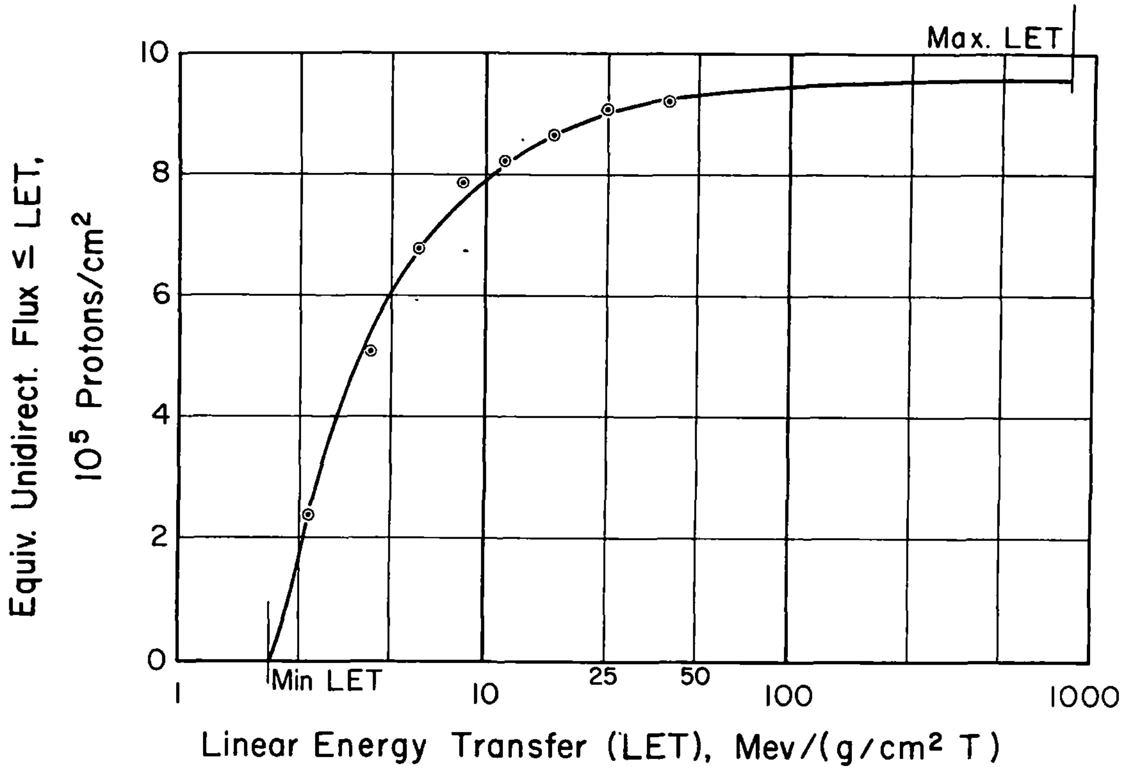

Figure 1

Integral LET Spectrum of Proton Flux in the G.5 Emulsion on
CSM Pilot's Chest

distribution is no longer possible. For the particular degree of development of the G.5 emulsion in Pack No. 1, as shown in Figure 2, the grain count of 180 grains/100 micra Em corresponds, for protons, to a kinetic energy of 12.25 Mev and a residual range in emulsion of 755 micra. The corresponding LET for tissue equals 39.8 Mev/(g/cm^{2}T). Although the mean LET for the class in question certainly must be larger than the just-named threshold value, the latter was selected for computing absorbed energy and dose. This was done in order to keep the dose fraction consistent with those of the preceding classes as well as with the enders count reported below. It should also be remembered in this connection that the precipitous increase of the LET in the Bragg peak is limited to a few micra of terminal section of the total residual track length of 755 micra belonging to the class in question.

An independent determination of the dose fraction for the class of lowest energy can be carried out with the aid of the enders count. This count was taken in a field of 6 x 6-mm area in the center of the K.2 emulsion in Pack No. 1. A value of 29.2 enders/mm^2 for an emulsion thickness of 200 micra before processing was found. Converted to tissue by applying a stopping power ratio of 2.0, this value corresponds to an

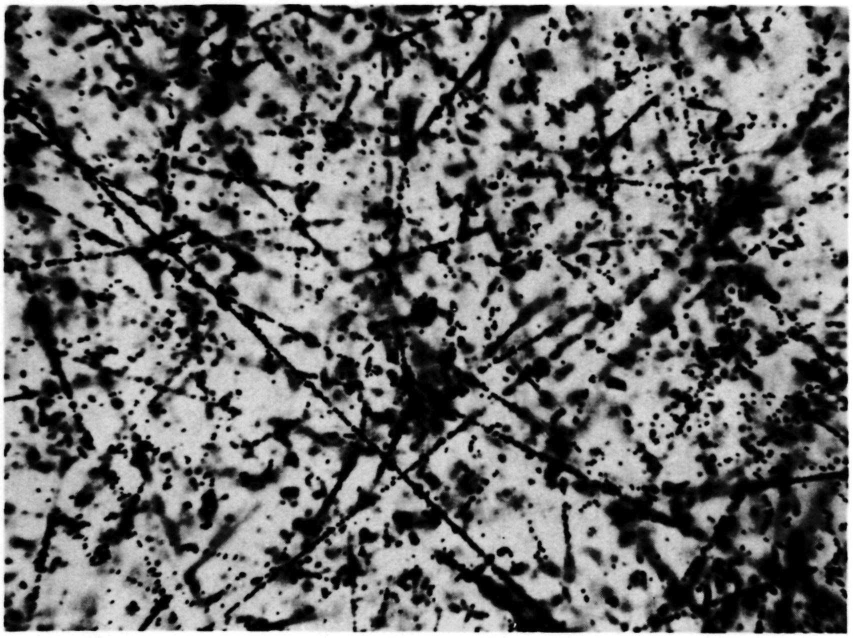

Figure 2

Typical Micrograph Taken from G.5 Emulsion on CSM Pilot's Chest

enders count of 73.1 enders per cubic millimeter tissue. Assuming even spatial distribution throughout the scanned volume and remembering that only the terminal section for which the grain count exceeds 180 grains/100 micra Em is to be taken into account, one arrives at an enders dose of 15.9 millirads.

The apparently large discrepancy between the values of 25.8 millirads from the grain count and 15.9 millirads from the enders count for the dose fraction from low energy particles finds its ready explanation in the fact that the former (higher) dose contains an unknown contribution from nuclei heavier than protons. Quite differently, the enders count contains strictly only protons because a proton ender can be very clearly distinguished from an alpha ender or a still heavier Z species in the K.2 emulsion. It is seen, then, that the agreement of the two dose values actually can be considered quite good, with the higher value most likely the correct one. In other words, we arrive at a total absorbed dose of 122 millirads for the Command and Service Module pilot's radiation exposure on Apollo VII. This value represents the integral mission dose received over a time period of 10.8 days in orbit. As mentioned before, the dose contains a certain fraction from alpha particles and heavier nuclei of galactic origin. While this fraction as such represents a large part of the galactic dose, it constitutes only a few per cent of the total recorded dose, which is made up mainly of protons. Earlier measurements of the galactic component on the Gemini VII mission (l.c., 3) have shown that the galactic exposure remains, in quantitative agreement with theoretical estimates, on the level of a few per cent of the dose from trapped protons for a near-Earth satellite orbit of low inclination. The reported exposure of 122 millirads, therefore, might as well be called the proton dose.

Although the remaining six packs were not subjected to track and grain counts, rather extensive enders counts have been conducted in the K.2 emulsions of all of them. As a rule, these counts were taken within a square of 6 by 6 mm exactly in the center of the emulsion sheet of 1 by 1.5 inch size. Table V shows the results of these counts. Since odd numbered packs contained 200-micra and even numbered ones, 100-micra K.2 emulsions, the enders counts in Column 2 of Table V have been normalized to 200-micra unprocessed emulsion thickness. However, the total numbers of identified enders listed in Column 3 are the true original scores; therefore, they can be used directly for assessing the statistical significance of the counts. It must also be mentioned that the scores in Column 3 are net values pertaining to true proton enders of the incident radiation. They do not contain star prong enders or neutron recoils as these two categories are rejected immediately by the observer in the scanning process.

Table V

Enders Count in Center of K.2 Emulsion for 7 Radiation Packs on Apollo VII

Pack No.	Enders Count, Enders/mm^{2*}	Total Number Counted
6	31.3	314
1	29.2	697
9	28.4	552
10	27.7	318
28	27.7	323
7	27.6	325
2	26.2	302

*For 200 micra thickness of unprocessed emulsion.

It should be emphasized once again that the differences in the enders counts in Table V cannot be considered as representative of the overall dose levels at the respective locations on the astronauts' bodies because the enders count shows, from square millimeter to square millimeter in the same emulsion sheet, larger fluctuations.

As mentioned before, these variations are partly of a statistical nature and partly reflections of true discontinuities in the shield distribution. A separation of the two effects is not possible because of the smallness of the absolute enders counts on this particular mission.

Attempts were made with a few emulsion sheets to augment the enders count in the center by counts in areas on opposite corners. At this time, these data are still incomplete. The largest difference so far was found in Pack No. 9. The K.2 emulsion of that pack shows an enders count of 21.5 enders/mm^2 in the upper left corner and a count of 31.1 in the lower right. As seen from Table V, the count in the center of the same sheet equals 28.4 enders/mm^2.

The direction of incidence of the enders was indicated, in the scanning process, in the plane of the emulsion by dividing the full circle in octants from NNE clockwise to NNW. The vertical direction was marked by the scanner merely as "from the air" or "from the Melinex" or "parallel." As far as the incomplete material accumulated so far allows conclusions, the directional anisotropies in all seven packs appear to be markedly smaller than those found on the Gemini missions. The strongest directional effect so far was found in the K.2 emulsion of Pack No. 7. Figure 3 shows the pertinent directional diagram. A slightly smaller effect was found in Pack No. 1 as shown in Figure 4. The reader is reminded that this is the same pack for which the full track and grain count analysis presented in this report holds. All other packs show only excursions from symmetry that remain within the range of statistical fluctuations. However, the scanning effort at this time does not yet fully cover the central areas in all packs.

Of special interest appears the finding that in all packs the differences in the numbers of enders from the air and from the film base, i.e., from the outside and from the astronaut's body, are insignificantly small and do not show any consistent preference for either direction of incidence. This result is quite reliably established as it is based on numbers of enders ranging from 300 to 700 for the individual film sheets, as can be verified from Table V. The finding is in sharp contrast to the conditions found on Gemini VII where a significant preponderance of enders from the outside prevailed in all packs. We are inclined to attribute the greater uniformity of incidence on Apollo VII to the much heavier shielding of the larger vehicle and to the fact that the crew in the Apollo vehicle had a larger freedom of movement. The two circumstances act together to make less prominent the influence of the self-shielding of the astronauts' bodies on the effective total shield distribution. A full clarification of the effect would require a better resolution of the zenith angles of incidence of the enders on the emulsion plane.

In summary it can be stated that, although the absolute dose level on Apollo VII is well in line with the one found on Gemini VII, the differences in the amount and distribution of shielding of the Gemini and Apollo vehicles seem to be reflected in a more uniform directional distribution of the low energy flux for the latter. A quantitative clarification of this effect would require a rather large scanning effort for which special arrangements would have to be made.

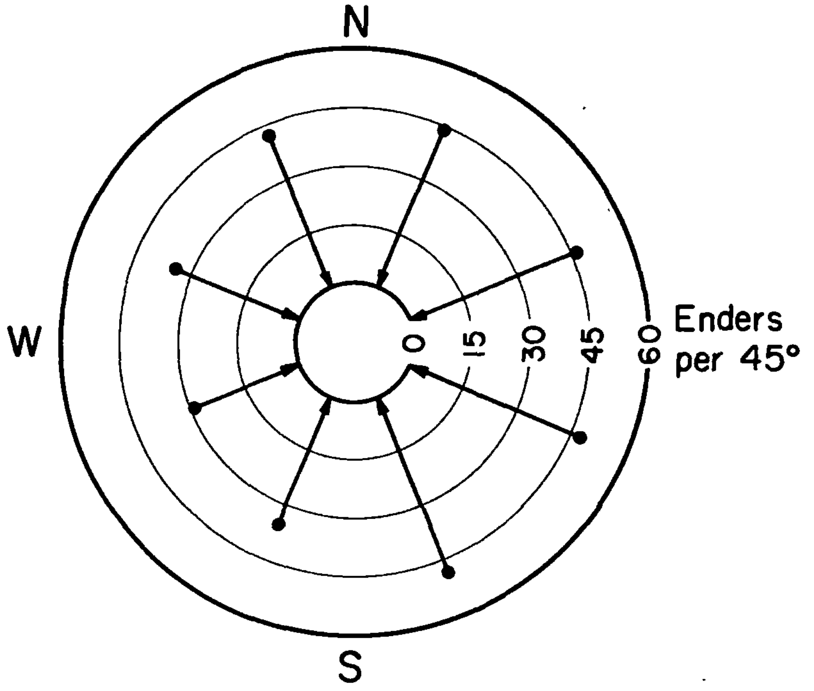

Figure 3

Directional Distribution of Proton Enders in K.2 Emulsion of Radiation Pack No. 7

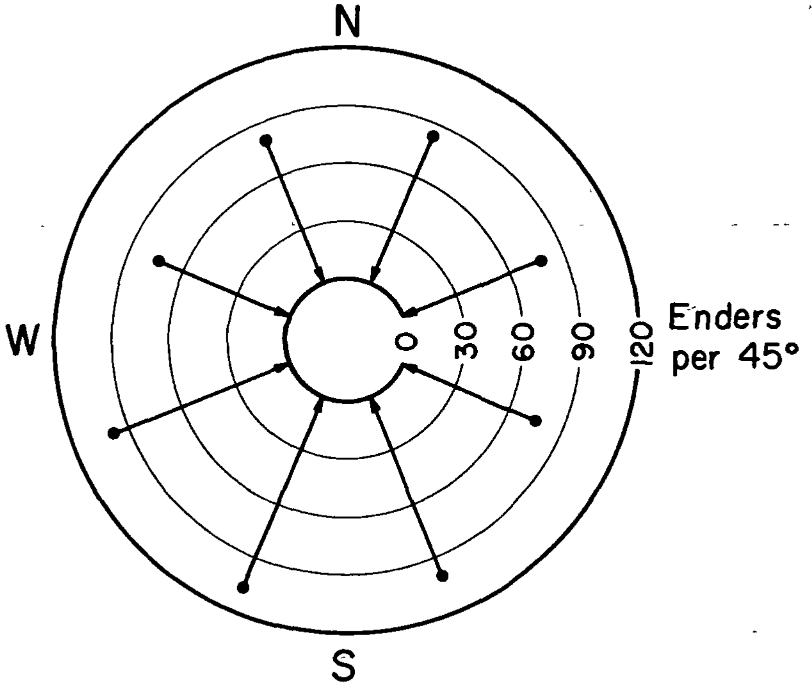

Figure 4

Directional Distribution of Proton Enders in K.2 Emulsion of Radiation Pack No. 1

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