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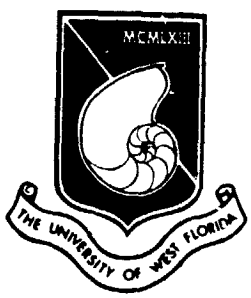

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FACULTY OF PHYSICS
THE UNIVERSITY OF WEST FLORIDA
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Hermann J. Schaefer

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Approved by

Alfred B. Chaet

Associate Vice President for
Research and Sponsored Programs

Released by

James A. Robinson

President
The University of West Florida

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Faculty of Physics
The University of West Florida
Pensacola, Florida 32504

SUMMARY

The bulk of the astronaut's radiation exposure in space is due to trapped protons and secondary neutrons, protons, and alpha particles from local nuclear interactions. The respective Linear Energy Transfer (LET) distributions are such that large fractions of the combined absorbed dose (AD) require Quality Factors (Q's) greater than 1.0 for converting AD's to dose equivalents (DE's).

A combined TLD/Emulsion method is proposed which measures the AD accurately with TLD (Thermoluminescent Dosimeter) chips yet merely samples the LET distribution with a plain proton ender count and the star frequency as anchor points. It is shown that the evaporation star model of Powell fits actual star and ender counts of past Apollo missions quite satisfactorily and that mission DE's can be assembled from combined TLD and emulsion data.

While the contribution of HZE particles to the AD is fully accounted for by the TLD readings, the DE cannot be determined because official rules and regulations do not define Q values for the extremely high LET of HZE particles. In the absence of such directions, it is proposed to sample the fluence of heavy particles by means of an HZE particle ender count and make it part of the exposure record for possible later interpretation.

INTRODUCTION

"Sampling Dosimetry" is a generic term denoting any method which records only selected representative parameters of a complex radiation field and establishes the total dose from known spectral characteristics. The particular method proposed in this study for Shuttle Orbiter operations would apply TLD (Thermoluminescent Dosimeter) chips and at least one sheet of nuclear emulsion. While the TLD component will record the absorbed dose (AD), the track population in the processed emulsion will reflect the particle make-up and Linear Energy Transfer (LET) distribution for determination of the mean Quality Factor (Q) and the dose equivalent (DE). The system has the unique advantage that the retrieval of emulsion data in the post-flight evaluation remains flexible within wide limits depending on the degree of accuracy and the corresponding scanning effort which one would want to select.

The method is an outgrowth of many years of experience gathered throughout the manned space programs from Mercury to Apollo-Soyuz. Public awareness and concern for radiation hazards have increased throughout those years while, at the same time, basic questions concerning the biological effects of low-level exposure to ionizing radiation have remained unanswered. Continued accurate record keeping of personnel exposures, therefore, would seem a mandatory requirement for future manned space operations. The proposed system attempts to simplify the complex monitoring methods used in the past to a more manageable level yet one which which still would meet minimum standards.

The use of nuclear emulsion containing the heavy elements silver (Ag, $Z = 47$, $A = 108$) and bromine (Br, $Z = 35$, $A = 80$) for tissue-equivalent (TE) dosimetry finds its justification in the particular make-up of the radiation environment in space. Produced almost exclusively by nuclear particles, the astronaut's radiation exposure can be established quite well in TE terms from the track population in an emulsion sheet placed on the body. In fact, nuclear emulsion appears uniquely qualified for the task because of the added advantage of furnishing a permanent record which can be read and re-read many times.

THE PROTON DOSE EQUIVALENT

Visualizing a sufficiently thin emulsion layer in a TE cover directly on the astronaut's body, one readily sees that particles of medium and high energies traversing the emulsion with little change in their respective energies produce a track population which reflects the true tissue dose in the body surface itself. It is also obvious that the origin of the particles, whether they are galactic or trapped primaries or locally produced secondaries, is irrelevant as far as the tissue dose is concerned.

Problems develop for particles of low energies, especially protons, entering the emulsion from the outside yet terminating within (so-called enders) because they do not fulfill the condition of insignificant energy loss in the emulsion. However, since the Stopping Power of emulsion for protons is about twice that of tissue, the frequency of proton enders in a tissue layer replacing the emulsion would simply be half the one recorded in emulsion and the DE can still be assessed accurately.

More complex is the problem with enders originating in so-called stars, i.e., in nuclear interactions occurring in the emulsion layer itself. About 75 per cent of all emulsion stars represent disintegrations of Ag or Br nuclei. That means their prong number distributions differ greatly from those of stars released in the gelatin matrix. Since the average prong number per star is higher for target nuclei with higher Z numbers, the contribution of Ag and Br stars to the total prong population is even substantially larger than 75 per cent. Star prong enders, therefore, have to be rejected in the ender count. This requirement has imposed, upon the complete emulsion scans of the past, a heavy penalty in man-hours at the microscope inasmuch as every ender not only had to be tallied but also traced back to its point of origin, sometimes through many visual fields. In sampling dosimetry, this time-consuming step is completely eliminated.

Because of its fundamental importance for the understanding of the interactions of the primary cosmic radiation with matter, the star phenomenon has been very thoroughly investigated. Powell, Fowler, and Perkins (1) have reviewed the subject with particular emphasis

on star formation in emulsion. Two types of disintegration stars are usually distinguished: evaporation stars resulting from nuclear interactions of primaries with energies up to several hundred Mev and knock-on stars packing higher energies up to many Gev. Reflecting the degraded local energy spectra of trapped and galactic protons, star counts in emulsions flown on manned missions have consistently shown disproportionately greater numbers of evaporation stars.

Powell and co-workers arrive at respective emission ratios of 8 to 4 to 1.6 for secondary neutrons, protons, and alpha particles from evaporation stars. They also present exact energy spectra for the three types of secondaries. The spectra have been reproduced in an earlier report (2) where they are applied to star counts of the Apollo-Soyuz mission. In a second report (3), the corresponding range spectra are presented and evaluated in terms of complementary probabilities for a star prong ending within the emulsion layer or leaving it.

For sampling dosimetry, a quantity of special interest is the mean prong number per star because it allows determination of the grand total prong number from the plain star count. That means the extremely time-consuming process of prong-counting every star is no longer needed. Table I summarizes prong count data collected in complete emulsion scans for six selected Apollo missions. It is seen that the mean prong number per star varies within acceptable limits about a grand total mean of 5.00 prongs per star.

It should be mentioned at this point that, in a normally developed Ilford K.2 emulsion, proton and alpha enders can be distinguished only if coherent track segments of at least several hundred microns are available. Shorter proton and alpha enders would appears differently only in a heavily underdeveloped K.2 emulsion. In the present context, where both kinds of enders are to be rejected, the lack of discrimination is of no consequence as long as the combined total number can be determined accurately. This condition can be met by applying the aforementioned probability of ending in emulsion to the undifferentiated total prong count which, in turn, is obtained as the product of the mean prong number per star and the star count.

Explicitly carrying out the just indicated operation, we go back to Reference 3 and find the respective probabilities for proton and alpha prongs ending within a 100 micron emulsion as 0.10 and 0.35. Weighting them with the relative abundances of 4 and 1.6 for proton and alpha prongs, we obtain a mean probability of $(4 \times 0.1 + 1.6 \times 0.35)/5.6 = 0.17$. In other words, 17 per cent of all prongs originating in stars in a 100 micron emulsion end within it. Naming the mean star frequency per mm^2 area of a 100 micron emulsion S and multiplying by the mean prong number per star of 5.0, we expect a total of $0.17 \times 5.0\ S = 0.85\ S$ star prong enders per mm^2. Table II shows that this theoretical frequency agrees well with actually recorded values for the star populations listed in Table I. In judging this statement one should remember that the theory of nuclear evaporation is based on thermodynamic analogies and cannot be expected to be accurate down to the last numerical detail. The proposed simplified method of assessing the frequency of star prong enders from the plain star count thus appears sound.

As mentioned above, enders originating in the material enveloping the emulsion represent legitimate contributors to the true DE in the body surface beneath the emulsion. It is obvious that the assessment of the DE from these enders does require specific information on the proton/alpha ratio. We approach this problem by assuming, as a first step, that all enders are protons, and then correcting, as a second step, for the additional DE from alpha prongs. Applying the relationships between range, energy, and LET for protons in tissue, we compute first the high-LET fraction for the full ender count. Official regulations assign Q's above 1.0 to LET values above 3.5 kev/ micron tissue. Protons exceed that threshold for energies below 10 Mev corresponding to path lengths of 560 microns in emulsion or 1370 microns in tissue. This shows that the high-LET fraction of a proton exposure is limited to the terminal sections of the tracks. It is seen, then, that the count of proton tracks, in sampling dosimetry, can be limited to enders since the total AD of the proton exposure is already accounted for in the TLD readings. Converting the official Q/LET relationship to the Q/E function for protons (shown in the lower graph of Figure 6 in Reference 5), we find by numerical integration a mean Q of 3.0 for a 10 Mev proton spending its full energy in tissue. Calling R the mean ender fre-

quency per mm^2 of 100 micron emulsion as it follows from the raw scores of the scan and correcting for star prongs, we obtain the true frequency N of enders entering the emulsion from the outside as N = R - 0.85 S. Since tissue has only half the Stopping Power of emulsion, the corrected ender frequency for tissue equals 0.5 N. Setting the energy dissipation of 1 Mev per cm^3 tissue equal to an AD of 0.016 microrads, we obtain the DE from proton enders as $D_p = 10^4 \times 10 \times 3.0 \times 0.5 \times 0.016$ N microrems = 2.4 millirems. Replacing the Q of 3.0 by 1.0, we find the corresponding AD as A_p = 0.8 millirads. The difference of the two quantities: $X_p = (2.4 - 0.8)$ N = 1.6 N milli(rems - rads) could be called the excess DE. It represents the quantity to be added to the AD for obtaining the DE. Since the AD is always accurately accounted for in the TLD readings, it is advantageous to express all high-LET fractions of the exposure in terms of their excess DE's.

THE ALPHA DOSE EQUIVALENT

The foregoing evaluation disregards the fact that a sizeable fraction of the ender population consists of alpha particles rather than protons. While many enders are trapped protons, i.e., true primaries entering the vehicle from the outside, others are secondaries from nuclear collisions, mostly evaporation events, in the local hardware, especially in the TE material of the dosimeter casing. These secondaries represent a mixture of protons and alpha particles in the ratio of 4 : 1.6 or 2.5 : 1.0. Since trapped protons and evaporation stars are essentially unrelated, the percentage of alpha particles can vary considerably depending on orbital parameters. Therefore, the percentage has to be determined separately from the star count.

Methods of assessing the fraction of gelatin stars in a population of emulsion stars have been reviewed in an earlier report (4). As pointed out there, the gelatin matrix occupies half the total volume of unprocessed emulsion yet accounts for only 26 per cent of the total cross section for star formation. That means 100 per cent gelatin offers only 52 per cent of the interaction cross section of an equal volume of emulsion. Furthermore, the mean prong number per star changes from 5.0 for emulsion stars to 3.7 for gelatin stars.

Less reliable is the available information on the neutron/proton/alpha ratio and the respective energy spectra for gelatin stars. The theory of nuclear evaporation applies thermodynamic concepts to the "gas" of nucleons in an excited nucleus after collision. That means the energy distribution of the nucleons "boiling off" are arrived at by statistical analysis. For Ag and Br with Mass Numbers of 108 and 80, the validity of the statistical model appears well assured. For nuclei with a mean Mass Number of 14, however, the applicability of the model is more limited. Nevertheless, with no experimental data on the energy spectra of secondaries from tissue stars available yet, a modified Ag Br star model offers itself as the only approach to an approximate solution. Above all, a downward adjustment of the mean number of neutrons per star appears indicated because of the smaller neutron/proton ratio in nuclei of lower Mass Numbers. However, no such adjustment would appear necessary for the proton/alpha ratio.

As we did before for evaluation of the high-LET fraction of the proton dose, we convert the official Q/LET relationship to the E/LET function for alpha particles in tissue and apply the latter to the energy spectrum of star-produced alpha particles shown in Figure 1 of Reference 2. Numerical integration furnishes a mean energy of 19 Mev and a mean Q of 10 for alpha prongs. As derived above, a total star count S in emulsion corresponds to a tissue star count of 0.52 S for equal volumes of the two media. A mean prong number of 3.7 for tissue stars and a proton/alpha ratio of 2.5 : 1.0 furnish a mean number of 1.06 alpha prongs per star or 5,500 S alpha prongs per cm^3 tissue. Multiplied by the mean energy of 19 Mev per prong, the frequency corresponds to an AD of 1.67 S mrads or, for a Q of 10, to a DE of 16.7 S mrems yielding an excess DE of 15 S milli (rems - rads). Since the 5,500 alpha prongs were treated erroneously as protons in the earlier assessment, the corresponding proton DE has to be subtracted. For an energy of 10 Mev and a Q of 3.0 per prong, we obtain a DE of 2.6 S mrems and an excess DE of 1.76 milli (rems - rads). We arrive, then, at a corrected excess DE of $X_a \sim 13$ S milli(rems - rads) for the alpha component.

THE NEUTRON DOSE EQUIVALENT

Evaporation stars do not only produce protons and alpha particles which are readily identifiable as visible prongs in emulsion, they also constitute a prolific source of fast neutrons. In fact, nuclear interactions in the local hardware and the astronaut's body account for the bulk of the neutron fluence in a space vehicle in orbit. Since the neutrons themselves do not leave any visible traces in emulsion and undergo, at the same time, an extremely complex process of energy degradation, exact determination of the neutron DE probably is the most difficult problem for radiation monitoring in space. The various aspects of the issue are examined in an earlier report (5). As pointed out there, the star count in emulsion offers itself as a workable compromise for a semi-quantitative assessment of the neutron DE if one wants to avoid the use of extraordinarily complicated instrumentation.

It has been mentioned above that, in assessing the tissue star dose from the star count in emulsion, the mean number of neutrons per Ag Br star should be reduced because of the smaller neutron/proton ratio of nuclei of TE material. A change of the neutron/proton/alpha ratio from 8 : 4 : 1.6 for emulsion stars to 6 : 4 : 1.6 for tissue stars should represent a well balanced estimate. We note that the revised ratio corresponds to a neutron/visible-prong ratio of 6 to 5.6. We obtain, then, for a mean number of 3.7 visible prongs, a mean number of 4 neutrons per tissue star.

Numerical integration of the energy spectrum of star-produced neutrons shown in Figure 1 of Reference 2 furnishes a mean neutron energy of 8 Mev. A count of S emulsion stars per mm^2 of 100 micron emulsion corresponds to a tissue star frequency of 5,200 S stars per cm^3 or a fluence of 20,800 S neutrons per cm^3 tissue. Applying the mean energy of 8 Mev and a Q of 10 and using the conversion factor of 1 Mev per cm^3 tissue equaling 0.016 microrads, we arrive at a neutron DE of 27 S mrems and an excess DE of 24 S milli(rems - rads).

Addendum after page 7:

It should be noted that the method of computing the local neutron dose by simply taking the number of neutrons generated per unit volume and multiplying them by their energies furnishes an upper-limit value which would be reached only in the interior regions of a large tissue phantom where equilibrium conditions prevail. For the energy spectrum of evaporation neutrons with 80 per cent of the fluence concentrated between zero and 10 Mev, the attenuation coefficients for tissue are such that the indicated equilibrium dose will be closely approximated in a target of the size of the human body. Moreover and most importantly, in establishing the neutron dose from tissue evaporation stars only, one completely disregards the neutrons from a number of other interactions within as well as outside the body. Therefore, the equilibrium dose from tissue stars is more likely to represent a lower-limit estimate of the total neutron dose.

CONCLUSION

Having determined the excess DE's for protons, alpha particles, and neutrons, we establish the total dose equivalent D by adding the three quantities to the total absorbed dose A as it follows from the TLD readings and obtain the expression:

$$D = A + X_p + X_a + X_n \quad \text{or}$$

$$D = A + 1.5\ N + 13\ S + 24\ S \text{ millirems.}$$

The alpha and neutron contributions of 13 S and 24 S are not consolidated to a single term because they have been arrived at in very different ways. While the alpha term is based on fairly reliable information concerning visible star prongs, the neutron DE is established from theoretical concepts and qualifies only as a semi-quantitative estimate. It is appropriate, then, to keep the two contributions separate for a realistic appraisal of their respective shares in the mission DE.

It seems of special interest to apply the proposed method, i.e., the just established formulas to the TLD readings and emulsion counts of the lunar missions in Tables I and II. The results are presented in Table III. Column 3 lists the TLD readings of the mission doses as they are reported in an official NASA publication (6). All other data are based on the counts of proton enders and stars in K.2 emulsions. The striking feature of Table III is the large contribution of tissue stars to the DE and, in turn, the large part of this contribution produced by neutrons. The fact that exactly the neutron DE can be assessed only from indirect evidence injects a note of discomfort and emphasizes once again the urgent need for further experimental work on the neutron problem (7).

Finally, an explanation is needed for the omission of the contribution of HZE particles to the mission DE. To be sure, the AD from the component in question is properly accounted for in the TLD readings. However, proceeding from there to the DE encounters the principal obstacle that official recommendations expressly exclude HZE particles from the application of conventional dosimetric concepts and units. It is sometimes suggested to apply a constant Q of 20 to all radiations with an LET above 175 kev/micron T. However, such

an evaluation would not at all do justice to the problem. Theoretical and experimental studies have made it abundantly clear that energy density rather than LET is the relevant magnitude for understanding and quantitating the action of HZE particles on tissue. Analyzed in terms of energy density, HZE particles are found to exceed the densities of conventional nuclear radiations only with smaller fractions of their total AD. Typical energy density distributions are presented in an earlier report (8). They show that abnormally high energy densities are limited to the terminal sections of the tracks. This circumstance suggests counting HZE particle enders as appropriate sampling technique similar to the count of proton enders. In the absence of official guide lines on permissible exposure, such a count should be made part of the exposure record for possible later interpretation when official recommendations will be set forth.

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TABLE I

Star and Prong Counts in Ilford K.2
Emulsion for Selected Apollo Missions

Mission	Stars Counted	Prongs Counted	Prongs/Star, Mean
Apollo 11	1180	6084	5.16
Apollo 14	585	2831	4.84
Apollo 15	852	4283	5.03
Apollo 16	404	2083	5.16
Apollo 17	1327	6365	4.80
Apollo-Soyuz	996	5050	5.07
Grand Total	5344	26696	5.00

TABLE II

Predicted and Observed Star Prong Enders
for Selected Apollo Missions

Mission	Stars/mm^2#	Star Prong Enders/mm^2#	
		Predicted	Observed
Apollo 11	4.57	3.88	4.88
Apollo 14	9.21	7.83	5.05
Apollo 15	6.94	5.90	7.61
Apollo 16	9.06	7.70	7.15
Apollo 17	11.2	9.52	7.36
Apollo-Soyuz	2.05	1.74	2.12

Area of 100 micron emulsion

TABLE III

Mission Dose Equivalents for Selected Apollo Missions
Established by Sampling Dosimetry

Mission	Duration, hours	Abs.Dose, millirads	Enders/mm^2	Stars/mm^2	Excess Dose Equivalent, milli(rems-rads) 1.5 N	13 S	24 S	Total	Mission Dose Equivalent, millirems
Apollo 11	195	173	18.5	4.57	27.8	59.4	110	197	370
Apollo 14	216	1142	66.0	9.21	99.0	120	221	440	1582
Apollo 15	295	300	40.5	6.94	60.8	90.2	167	318	618
Apollo 16	266	500	49.0	7.52	73.5	97.8	181	352	852
Apollo 17	301	600	56.0	13.5	84.0	176	324	584	1184

Absorbed Doses in Column 3 taken from Ref. 6.