Radiation Monitoring on Project Mercury: Results and Implications

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ABSTRACT

For the limited altitudes and times in orbit of the Mercury Missions, no objectionable radiation exposure of the astronaut was likely to occur. The objective of radiation monitoring, therefore, was limited to obtaining a post-flight record of the exposure during the mission. Since ionizing radiation outside the atmosphere consists predominantly of nucleons with only a negligible addition of gamma rays and electrons, a small nuclear emulsion pack seemed the most appropriate radiation sensor for the indicated purpose.

On Missions MA-8 and MA-9 two special circumstances called for closer attention to radiation exposure. These were the artificial radiation belt of electrons created in the high altitude nuclear explosion of July, 1962 (Starfish Test) and the residual proton flux of the Inner Van Allen Belt reaching down to satellite altitudes in the South Atlantic Anomaly. Earlier missions had not encountered either hazard because they were completed prior to the Starfish Test and consisted only of three orbits and therefore stayed clear of the South Atlantic Anomaly.

Ilford G-5 emulsions flown on MA-8 and MA-9 showed a background from electrons and gamma rays not significantly different from that of the sea level controls indicating that the inherent shielding of the capsule was sufficient for complete absorption of electrons from the artificial radiation belt. The emulsions did show large populations of low energy protons picked up in the South Atlantic Anomaly. Evaluation by track and grain count furnished the differential energy spectrum of these protons and lead to an absorbed dose of 27 millirads, an RBE dose of 31 millirems, and a QF dose of 41 millirems. The additional exposure from all other sources, i.e., from heavy nuclei, distintegration stars, and meson events is estimated at 2 millirads.

The most significant result of the measurements is the absence of electrons and gamma rays as contributors to the additional dose in the flown emulsions as compared to the sea level controls. It indicates that the primary cosmic ray beam produces, in one and a half tons of compact material of the Mercury capsule, only an insignificant amount of electrons and gamma rays.

WHEN THE QUESTION of a suitable method for recording the radiation exposure of the astronaut on Project Mercury arose, it was quite obvious from the beginning that, for the limited duration and the limited orbital altitude of the Mercury Missions, the radiation dose would remain far below any objectionable level. In-flight measurement of dose rate or in-flight read out of accumulated dose, therefore, seemed definitely dispensable. On the other hand, monitoring the radiation exposure of the astronaut on each mission seemed desirable for a complete record of all environmental parameters.

For Missions MA-8 and MA-9, two special problems arose which called for closer attention to the radiation exposure. Missions MA-8 and MA-9 took place within one year after the high altitude nuclear explosion known as the Starfish Test. Beta rays from this explo-

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This work was conducted under the sponsorship of the Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas.

Opinions or conclusions contained in this report are those of the author. They are not to be construed as necessarily reflecting the view or the endorsement of the Navy Department.

Presented at the Aerospace Medical Association annual meeting in Miami Beach, Florida, May 13, 1964.

sion had created a strong artificial radiation belt of electrons reaching down to normal satellite altitudes. Uncertainties and discrepancies in the prediction of experts concerning flux values, energy levels, and decay times of the artificial radiation belt left those responsible for the safety of the astronaut essentially without reliable information on which to base a decision whether in-flight read out of accumulated exposure would be necessary. Such instrumentation actually was provided for Mission MA-8; however, it turned out that the exposure from electrons remained entirely on the level of the ionization dosage from the ordinary cosmic ray beam.

The second problem concerned the additional exposure on MA-8 and MA-9 in the so-called South Atlantic Anomaly, a region over the South Atlantic where the mirror points for protons of the Inner Van Allen Belt dip down more deeply than at any other longitude due to certain irregularities in the structure of the earth's magnetic field.[2] The three orbits of Glenn (MA-6) and Carpenter (MA-7) stayed clear of this region. However, since the longitude of the nodes changes by about 25° per orbit due to the rotation of the earth, the last three of the six orbits of MA-8 and some ten of the 22 orbits of MA-9 scanned through the central or peripheral regions of the Anomaly. The added proton flux from this exposure showed up quite clearly in the emulsions of Missions MA-8 and MA-9.

Ionizing radiation outside the atmosphere consists predominantly of nucleons with only a negligible addition of gamma rays and electrons. In view of this fact, the principle of tissue equivalence for measuring the absorbed dose in rad units is not applicable. For particles such as protons, alpha particles, or heavy nuclei producing ionization in tissue, the concept of an equilibrium between electrons from the primary beam and from scattered radiation as in the case of x- or gamma rays is meaningless. Therefore, indirect determination of absorbed dose from measurements of the local particle flux and its LET (Linear Energy Transfer) spectrum by means of nuclear emulsion is a better approach than any attempt to design a tissue equivalent sensor which would indicate absorbed dose directly. Admittedly, the heavy elements silver and bromine in nuclear emulsion will produce secondary nucleons in nuclear interactions which will have different characteristics from those that would originate from the light elements in tissue. However, if the total emulsion volume is small enough to ensure that the bulk of the particle flux recorded in the emulsion enters from the outside, the contribution from nuclear interactions with the heavy elements in the emulsion will also be small.

The foregoing proposition becomes invalid if a significant fraction of the radiation incident upon the emulsion consists of x-, beta, or gamma rays. These ionizing agents do not produce, in emulsion, distinct straight tracks but cause merely a general increase of background density. Yet this density is not related directly to absorbed dose in tissue. The same density produced by x- or gamma rays of different energies corresponds to greatly different absorbed doses in tissue expressed in rads. The criterion, then, whether an exposure of nuclear emulsion can be evaluated in terms of absorbed dose in tissue would be whether it consists predominantly of particle tracks on a low background or of a few tracks on a dense background. Fortunately, the nuclear emulsions on all Mercury flights retained a very low background which never differed significantly from that of the sea level controls.

The so-called standard emulsion pack used on all Mercury flights consisted of 8 nuclear plates of 1 by 3 inches of Ilford G-5 and K-2 emulsions of 50, 100, an 200 micra thickness in varying combinations. The plates were wrapped in black paper, aluminum foil, cardboard, and epoxy resin representing a maximum of almost 1.0 gram per centimeter material for particles entering at right angle to the emulsion plane and of about 0.3 g/cm^2 at the 1-inch edge of the plates. These different equivalent thicknesses at different sides of the pack in connection with the glass support of the emulsions provided a wide range of different prefiltration values for individual emulsion areas which would have allowed identification of any soft radiation component. Electrons in particular, entering at the minimum prefiltration side of the pack, would have produced a gradient of the background density in the emulsions from the edge toward the inside. In no instance has such a soft radiation component been found. One might say that this was to be expected since any radiation entering the capsule undergoes heavy prefiltration in the vehicle wall and equipment.

The problem of evaluating a population of particle tracks recorded in a nuclear emulsion might be explained with the aid of Figure 1. It shows a composite photomicrograph of a sectional area of an Ilford G-5 plate flown on Mission MA-9. Two very heavy tracks

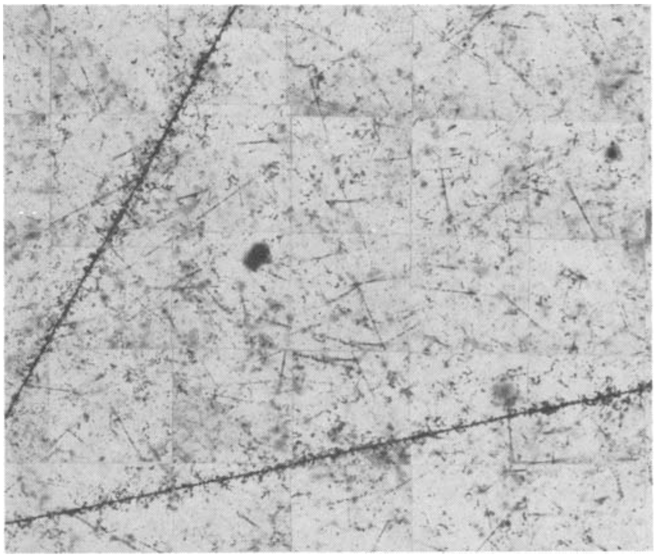

Fig. 1. Composite photomicrograph of Ilford G-5 emulsion flown on Mission MA-9. Picture shows two heavy nuclei tracks of estimated Z = 14 (lower) and 18 (upper left) and many tracks of protons of different grain densities. Picture is typical for proton population, but is atypical with regard to heavy tracks since their flux is low and a combination of two of Z > 10 in close vicinity quite seldom occurs. Note low background of beta and gramma rays.

from nuclei of an estimated Z = 14 and 18 stand out clearly on a background of a large population of light tracks, most of them protons. The micrograph also shows clearly the low general background of single grains and of tortuous tracks and grain clusters from electrons. As mentioned before, this low general background indicates that the ionization dosage is to be attributed mainly to the nucleonic component with a beta-gamma background not significantly different from that at sea level.

If a population of tracks is to be evaluated in terms of absorbed tissue dose in rads, it is necessary merely to know the total track length per unit volume and the LET distribution. Identification of Z-numbers of tracks is not necessary. This distinguishes the task of the radiobiologist, who is interested in absorbed dose in tissue, from that of the physicist, who is interested in complete information on type of particle, number, and energy spectrum of a flux. The LET of a proton in nuclear emulsion can be determined by grain counting. Figure 2 shows 8 selected proton tracks from G-5 emulsions flown on MA-8 ranging in grain count from 23 to 240 grains/100 micra emulsion. For still higher grain densities, i.e., lower particle energies, grain counting becomes increasingly more difficult and inaccurate and finally impossible when the individual grains coalesce, in their optical appearance under the microscope, into a coherent black line (so-called black tracks).

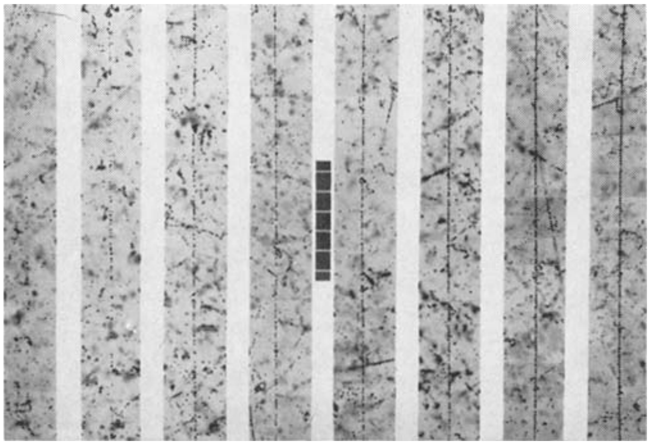

Fig. 2. Selected proton tracks from Ilford G-5 emulsions flown on Mission MA-8. Grain density from left to right is: 23, 52, 77, 108, 120, 155, 203, 240 grains per 100 micra. 1 scale division = 10 micra.

The just-mentioned limitation in the quantitative evaluation of a proton track population can be overcome by the count of so-called "enders," i.e., of protons ending in the emulsion. It is obvious that an ender represents a proton of zero energy. The enders count, then, defines the low end of the energy specturm, i.e., the other end of the gap within which grain counting is not possible.

Applying the just-described method of combined evaluation of the grain and enders count to the protons in the emulsions flown on MA-9 leads to the differential energy spectrum shown in Figure 3. Since it is the local spectrum of the proton flux in the emulsions and since the emulsion pack was shielded by a combined thickness of material equivalent to the shielding of the astronaut's body, the spectrum can be interpreted directly in terms of absorbed dose by assuming that the same flux would enter the body of the astronaut. In this transfer, merely the different stopping powers of emulsion and tissue have to be taken into consideration in computing the absorbed energy per unit volume.

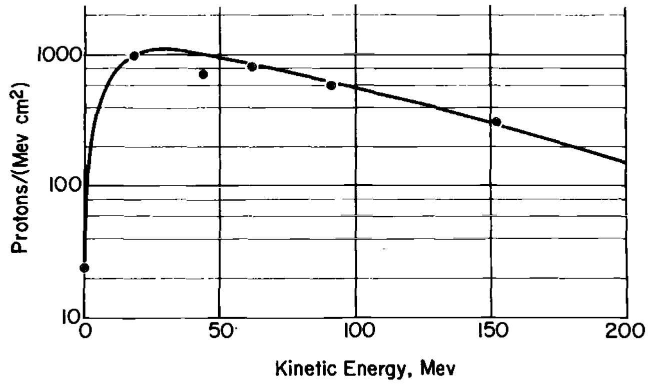

Fig. 3. Differential energy spectrum of proton exposure on Mission MA-9. Shown is local spectrum directly as it corresponds to track and grain count in the emulsions. Ordinate gives total flux for entire mission: 22 orbits, 35 hours.

Since the number of ion pairs which a proton produces per unit length of travel in tissue depends strongly upon its energy, the evaluation of the differential energy spectrum in terms of absorbed dose has to be carried out by breaking it down into narrow energy intervals within which the energy dissipation can be considered constant. If these contributions to the total dose are added up beginning at zero energy, one obtains the graph of the cumulative dose of Figure 4 which shows not only the total dose, but conveys also information on the size of the individual contributions. It is seen that the steepest build-up of cumulative dose occurs at low energies, indicating that in this region the fractional dose per Mev is largest. At the

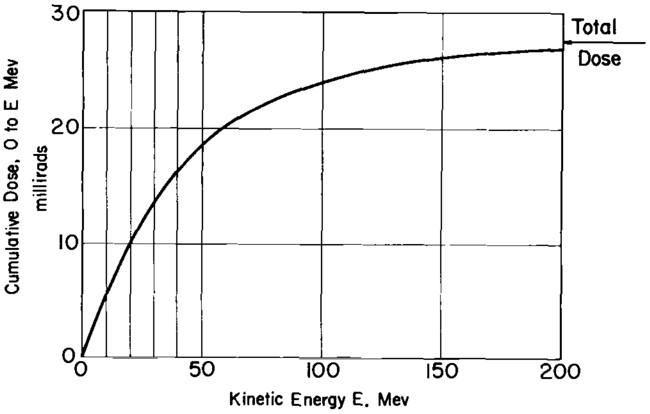

Fig. 4. Cumulative dose versus proton energy on Mission MA-9.

other end, beyond 200 Mev, the contributions per Mev become very small. In fact, the cumulative dose quite closely approaches the total dose at 200 Mev. This indicates that even major errors in the track count at this energy and beyond, i.e., at low and very low grain densities, would produce only minor changes in the total proton dose of 27 millirads.

For a full appraisal of the exposure hazard, the absorbed dose in millirads has to be converted into the dose equivalent in millirems. For this conversion, Relative Biological Effectiveness (RBE) and Quality Factor (QF) have to be determined. For a radiation of spectral composition shown in Figure 3, this requires again separate determination of RBE and QF for each energy interval since the energy dissipation, i.e., the LET is different for each interval. The details of this analysis have been presented in earlier studies.[7, 8] In the latest recommendations of the RBE Committee to the ICRP and ICRU,[6] formulae are set forth directly relating RBE and QF to LET. Using these formulae, we obtain, for the differential energy spectrum of Figure 3, a mean RBE of 1.15 and a mean QF of 1.52. Applied to the absorbed dose of 27 millirads, this leads to an RBE dose equivalent of 31.1 millirems and to a QF dose equivalent of 41.3 millirems.

A particular problem exists concerning the interpretation of the heavy nuclei count in terms of radiation damage. On the one hand, the total ionization dosage from heavy nuclei expressed in the usual way in millirads, i.e., in absorbed energy per unit tissue mass is extremely small. On the other hand, it seems quite questionable whether this expression is realistic and meaningful since the absorbed energy is concentrated, in the micro-structure of tissue, in a cylindrical volume of about two cells diameter, in which the dose from a single traversal amounts to hundreds and thousands of rads. Several investigators[1, 4] have produced experimental evidence that such cells in the direct pathway of a heavy nucleus are indeed severely damaged. No data are available, however, on how acute or long-term damage would develop in multicellular organisms from total body exposure to such "microbeam" irradiation.

All that seems left to do under these circumstances is to identify the heavy tracks in the flown emulsions and to compare their count with the theoretical value. Estimates of Z values of heavy nuclei are possible by comparing the diameter of the solid silver core and the delta ray aura of an unknown track with tracks of relativistic nuclei of known Z-number. A calibration scale of this kind covering the Z-numbers from $Z = 1$ to $Z = 26$ (Fe) for Ilford G-5 emulsion has been published by Powell, Fowler, and Perkins.[5] This indirect method seems acceptable as a rough estimate, especially for exposures to the primary cosmic ray beam at low latitudes where the magnetic field of the earth admits only high energy nuclei. If one uses the energy spectrum for heavy nuclei suggested by Singer[9] as the best representation of all existing experimental data, the integral heavy flux per orbit can be computed by numerical integration, taking into consideration the dependence of the minimum energy of arrival on varying geomagnetic latitude for the trajectory of a Mercury orbit. For the twenty-two orbits of Mission MA-9 this computation leads to a grand total of twenty-seven traversals of a target area of 1 cm^2 by nuclei of a $Z \geq 10$ assuming isotropic hemispherical incidence. Classifying the heavy tracks in the MA-9 emulsions by the indicated visual comparison, we obtain a slightly smaller track count of $Z \geq 10$. In view of the large margin of error inherent in this method, we cannot state with certainty that this smaller flux inside the ship is real and indicative of a narrowing of the solid angle of particle acceptance due to local attenuation effects.

For the lower part of the heavy spectrum comprising the Z-numbers from 3 to 9, track identification by visual comparison is still less reliable. We are, therefore, unable to differentiate the track population in the flow emulsions and can only estimate in general that the track count is of the order of magnitude of the flux of the incident beam. Summarizing the emulsion findings of the entire heavy component, it could be said, then, that the dose contribution can be assessed on the basic of the flux values for the incident beam. This dose of the incident beam, computed under consideration of the latitude scan of a Mercury orbit, amounts for the thirty-five hour exposure on Mission

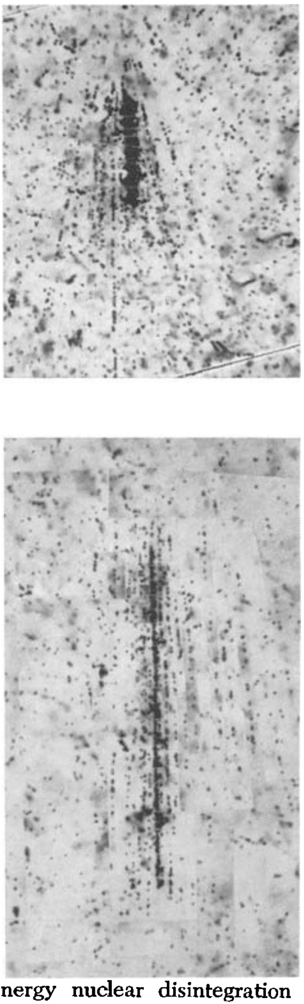

Fig. 5. High energy nuclear disintegration showing narrow and wide angle meson cones in two adjacent Ilford G-5 emulsions flown on Mission MA-7.

MA-9 to slightly less than one millirad. The smallness of this dose demonstrates that an accurate Z differentiation of the heavy spectrum, which would require quite large emulsion volumes, is of no importance for the assessment of dose from heavy nuclei on Mercury type missions.

In addition to heavy nuclei, the flown emulsions show other nuclear interaction events characteristic of the extremely high energies of cosmic ray primaries. The population of multipronged evaporation stars has been evaluated thoroughly with regard to prong number of stars per unit emulsion volume. This reaction is typical for the heavy elements Ag and Br of which nuclear emulsion contains about 85 per cent by weight. In organic matter and living tissue, which are practically devoid of heavy elements, star formation accounts for only a negligible contribution to total dose. A detailed account of the data on the star population, therefore, is omitted here.

Nuclear interactions at extremely high energies beyond the meson production threshold are still, by an order of magnitude, less frequent than star disintegrations. Moreover, most of their singly charged secondaries are counted with the proton component. That means their contribution to absorbed dose is correctly accounted for. The most spectacular event of this type, recorded on MA-7, identified in two adjacent emulsion layers, is shown in Figure 5.

If we try to summarize the results of the radiation monitoring of the Mercury flights with special emphasis on the implications for dosimetry of ionizing radiation in space in general, the most important finding is the fact that in all cases, even in the thirty-five hour exposure of MA-9, the G-5 emulsions retained a beta-gamma background essentially equal to that of the sea level controls. This proves that, in the space ship, the exposure in excess of the sea level background is mainly due to the nucleonic component. This, in turn, allows the conclusion that the close vicinity of almost one and a half tons of scattering material about the emulsion pack and the astronaut does not produce a significant contribution of beta or gamma rays. There are good reasons to assume that local scattering does produce a substantial contribution to the nucleonic component in the form of neutrons and protons. In this respect it might be emphasized again that there is no possibility of identifying this contribution, i.e., of distinguishing in the total proton population, the primaries from the secondaries. However, as pointed out before, for the determination of dose this uncertainty is entirely irrelevant as long as the ionization dose of the particles is correctly assessed.

How far this characteristic feature of a very low beta-gamma background would be preserved in exposures of very large ships to solar particle beams cannot be concluded from the Mercury data. Emulsion recordings of solar proton beams with high altitude ballons[3] indicate consistently that the bulk of the ionization dose is, in very much the same way as in the emulsions of MA-8 and MA-9, predominantly due to protons.

Except for this reservation concerning very large ships in solar particle beams, the radiation monitoring with nuclear emulsions on the Mercury flights has proven that the astronaut's exposure can be assessed reliably in terms of absorbed dose in millirads and of dose equivalent in millirems with very small emulsion volumes. It should pose no problem to design an even smaller unit than the standard emulsion pack by discarding a large part of the wrapping and casing material and by changing from plates to pellicles. Such packs could be inserted at several locations inside the astronaut's space suit and would provide essentially the same information as the standard emulsion pack did on the Mercury Missions.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of Jeremiah J. Sullivan, physicist, throughout the entire project.

The author is greatly indebted to F. C. Maienschein and R. T. Santoro of Oak Ridge National Laboratory for exposing test plates to 450 Mev protons at the Chicago Synchrocyclotron. The large workload of scanning the emulsions was aptly handled by M. G. Basha, D. A. Cormier, C. N. Coulter, E. T. Nelson, S. A. Sweeney, and R. C. Symington. The excellent microphotographic evaluation of the material was done by M. G. Basha.

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