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RADIATION MONITORING ON PROJECT MERCURY: RESULTS AND IMPLICATIONS*

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Under contract with the Manned Spacecraft Center of the National Aeronautics and Space Administration, the U.S. Naval School of Aviation Medicine carried out radiation monitoring on all Mercury flights. It was quite obvious from the beginning that, for the limited duration of exposure and the limited orbital altitudes of the Mercury Missions, the radiation exposure of the astronaut would remain far below any objectionable level. In-flight measurement of dose rate or in-flight follow-up 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 problems arose which called for closer attention to the radiation exposure. Both missions took place within one year after the high altitude nuclear explosion known as the Starfish Test. Beta rays from this explosion had created a strong artificial radiation belt of electrons reaching down to normal satellite altitudes. Uncertainties and discrepancies in the predictions 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 follow-up of accumulated exposure would be necessary. Such instrumentation actually was provided for Mission MA-8; however, it turned out that within the ship the exposure from electrons was not significantly higher than the normal ionization dosage from the ordinary cosmic ray beam.

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

The composition of the primary cosmic ray beam outside the atmosphere and its dependence on geomagnetic latitude is fairly well-known. It would appear basically an easy task, then, to establish a close estimate of the exposure per orbit by theoretical computation. The shortcoming of this approach rests in the fact that the astronaut's body is surrounded by one and a half tons of compact material made up of the vehicle frame and equipment. In this material, the primary cosmic ray particles undergo complex transition processes partly resulting in attenuation, i.e., in a decrease of exposure, but to a much larger degree resulting in particle multiplication through production of secondaries in nuclear collisions thereby substantially increasing exposure. To be sure, in terms of millirem dose, this exposure will still remain far below any objectionable level even if a factor of 2 or 3 or even 5 would be used for estimating the additional exposure from secondaries.

Considering the just-mentioned circumstances and the general conditions of the Mercury Missions, the most suitable choice of a radiation sensor appeared to be nuclear emulsion. Its extremely high sensitivity and its ability to identify ionizing particles individually, in combination with the fact that it works truly "automatically" without any power supply or electronic or mechanical device, gave it a clear preference for missions on which weight economy was a particularly pressing demand and no compelling reason for in-flight information on the exposure status existed.

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, and 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.

Estimates of the total exposure from the primary cosmic ray beam lead, even for several orbits, to very small dosages below the 10 millirad level even if a factor of 2 is used for the local scattering effect. This is well borne out by microscopic examination of the G-5 emulsions. They show a general background from electrons and gamma rays which does not significantly differ from the sea level controls. The flown plates show, superimposed on this background, small populations of singly charged particles, heavy nuclei, and multipronged disintegration stars.

This picture changed in the emulsions flown on MA-8 and MA-9. Even a perfunctory microscopic examination revealed immediately the presence of an unusually large population of protons of lower energies well in excess of what would correspond to the larger exposure time for 6 (MA-8) and 22 (MA-9) orbits as compared to 3 orbits of earlier missions. Since the lowest geomagnetic cutoff energy for cosmic ray protons for an orbit of 30° inclination is well above 1 billion e-volts, low energy protons could originate only locally in the capsule from nuclear interactions of high energy primaries. However, interactions of protons of such very high energies produce mesons and cascade protons and neutrons rather than low energy nucleons. Quite differently, trapped protons in the South Atlantic Anomaly have energies below the minimum energy for meson production and will release, in nuclear collisions, predominantly low energy protons and neutrons.

An individual identification of the fractions of the total proton population in the emulsions, which are primaries or secondaries from trapped protons or secondaries from high energy interactions of cosmic ray protons in the local hardware of the ship is not possible. It should be pointed out, however, that this identification is entirely irrelevant as far as the determination of the exposure dose is concerned. As long as the track population in the emulsions is representative of the corresponding population penetrating the astronaut's body, and as long as the absorbed energy and the dose equivalent of this population is accurately determined, the dosimetric objective is fully met.

Microscopic track evaluation is a tedious and time consuming task. For a full assessment of exposure, not only the number and total length of tracks per unit volume of emulsion, but also the grain density of each track have to be recorded separately. Since grain density depends directly, though not linearly, on the ionizing power of the particle, the combined track and grain count ultimately furnishes the absorbed energy per unit volume, i.e., the radiation dose. A limitation of the method rests in the fact that for protons of very low energies, because of their large ionizing power, the grains are too densely space to be individually identified and counted. This difficulty can be overcome with the count of so-called "enders," i.e., of proton tracks ending in the emulsion.

The evaluation of the proton track population in the emulsions of Mission MA-9 by the indicated method leads to a total dose of 27 millirads. For a full appraisal of the exposure hazard, this absorbed dose of 27 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 heterogeneous radiation consisting of particles of different ionizing powers or, in radiobiological terminology, of different Linear Energy Transfer (LET), the LET distribution has to be determined and the corresponding RBE and QF distribution have to be established. If this evaluation is carried out using the latest recommendations of the RBE Committee to the International Commission on Radiological Protection, the proton dose of 27 millirads corresponds to an RBE dose equivalent of 31 millirems and to a QF dose equivalent of 41 millirems.

On Mission MA-8, which consisted of 6 orbits, two separate emulsion packs were flown, located at different positions, yet both in close vicinity of the astronaut and with no interposed equipment. Pack I showed a net exposure from protons of 7 millirads and Pack II of 21 millirads. We attribute this large difference to local shielding effects which lead, during the critical passes of the capsule through the South Atlantic Anomaly, to different exposures of the two packs. For the particular range of penetrating powers as they correspond to the energy spectrum of the proton population in the emulsions, such a difference in the effective shielding toward the hemisphere of the sky for two different locations is quite plausible.

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 have produced experimental evidence that such cells in the direct pathway of a heavy nucleus are indeed severely damaged. However, no data are available 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 compare their count with the theoretical value. From existing experimental data on the energy spectrum of heavy nuclei, the integral heavy flux per orbit can be computed by taking into consideration the dependence of the minimum energy of arrival on the latitude scan for the trajectory of a Mercury orbit. For the 22 orbits of Mission MA-9, this computation leads to a grand total of 27 traversals of a target area of 1 cm^2 by nuclei of a $Z \geq 10$ assuming isotropic hemispherical incidence. The actual count of heavy tracks in the MA-9 emulsions is slightly smaller. However, in view of the relatively large margin of error in estimating Z-numbers of tracks from their visual appearance, 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.

In addition to heavy nuclei, the flown emulsions show other nuclear interaction events characteristic of high energy cosmic ray particles. The population of multipronged evaporation stars has been evaluated thoroughly with regard to prong number distribution and 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 of extremely high energies beyond the meson production threshold are still 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 additional dose from all sources other than protons, i.e., from heavy nuclei, disintegration stars, and meson cones, is estimated at less than 2 millirads. About 1 millirad of this dose is due to the heavy component and should be carried separately in the records because it is equivalent to a "microbeam" irradiation which cannot be adequately measured in terms of absorbed dose.

It seems of interest to point out that the emulsions of all missions, even in the 35-hour exposure on MA-9, retained a beta-gamma background essentially equal to that of the sea level controls. This proves that, in the 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 ton 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 these 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 balloons and smaller rockets 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 all 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.