Recommended Ionizing Radiation Exposures For Early Exploratory Space Missions

S. J. Baum, Ph.D.

SPACESHIPS designed for early exploratory missions will probably not be sufficiently shielded to protect astronauts completely from the high energy proton radiations produced by solar flares. However, before man ventures into the unknown hostile space environment, a radiation exposure dose must be decided upon and shielding must be designed which will indicate a high probability that astronauts will be protected from nearly all ionizing radiations in excess to that dose. The size of this new permissible exposure dose for early missions will be higher than that presently permitted for radiation workers, nevertheless, it must be low enough to prevent acute biological effects which in turn might influence the space pilot's capability to perform his task.

Furthermore, since the training of space pilots is rather expensive, some probability must be established that they would participate in a number of voyages. From the radiobiological point of view, this would only be feasible if the initial exposure dose is within the new permissible area, if sufficient time is permitted for biological recovery and, finally, if the accumulation of residual damage to vital organs and tissues has not been too great.

The present study presents an analysis of the above listed biological parameters with the view of proposing a realistic exposure dose for early missions and a computed estimate of the possible number of "permissible" exposures to such radiation doses.

RADIATION INJURY TO MAN

Figures 1 and 2 indicate the radiobiological effects upon humans from either deep penetrating ionizing radiations or from those of lower energies which are absorbed at the skin surface. Since solar flares are comprised of a heterogeneous beam of low and high energy protons and electrons both concepts must be considered. As may be seen from Figure 1 penetrating radiation doses up to 125 rads should on the average not result in any disease symptoms to man. The skin probably will absorb several thousands of rads (Fig. 2) before it would acutely affect astronauts. In general, it can be assumed that depending on proton energy distributions, severe incapacitation from the penetrating radiations would occur before similar effects of the surface hazards would be noticeable. The latter would then at best only compound the former. It is known that the dose absorbed by the bone marrow, the site for blood cell production, will probably be limiting in terms of disease and lethality. The main concern is then the ionizing radiation absorbed by this organ, followed in order of magnitude by damage to the gastrointestinal cells, the gonads, the germinal epithelium of the skin and finally at doses of several thousand rads of penetrating radiations the central nervous system.

In summary, then, disease symptoms will become apparent at penetrating dose levels of approximately 125 rads, will increase in severity with increasing exposure and probably fatality (5 per cent level) will commence at an absorption of approximately 250 rads. However, it must be strongly emphasized that this does not mean that injury is not received below a dose of 125 rads. As a matter of fact a decrease in white blood cells can be measured after an exposure as low as 25 rads. Furthermore, animal experiments have demonstrated that exposures up to 100 rads will definitely result in late symptoms, such as tumors, cancers and a general

From the Life Sciences Section, Missile and Space Systems Division, Douglas Aircraft Company, Inc., Santa Monica, California

decrease in life span. The above statement may only be construed to mean that up to a dose of 125 rads no overt symptoms will make their appearance which could incapacitate astronauts.

THE DEEP HAZARD OF PENETRATING RADIATION

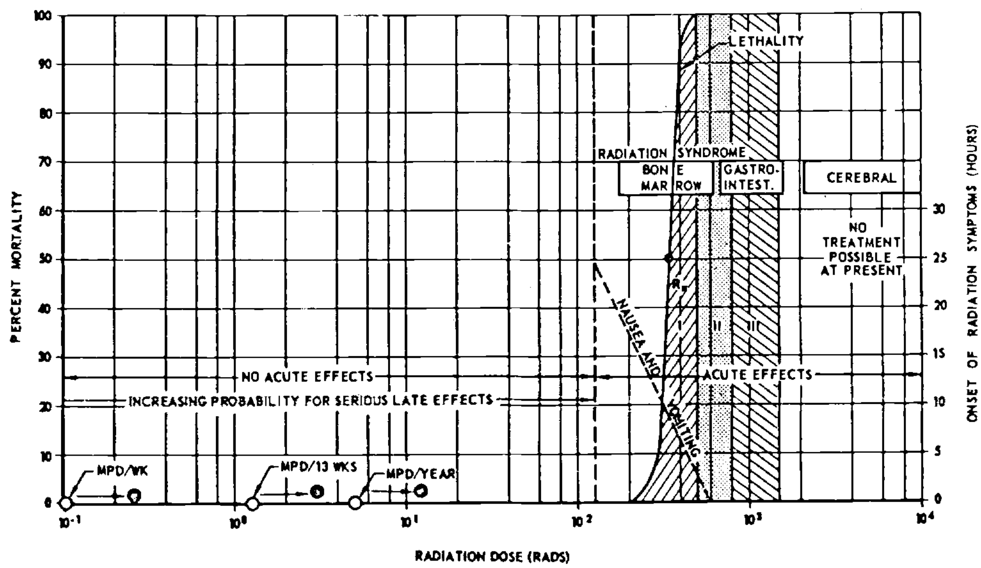

Fig. 1. Injuries inflicted to man by increasing doses of penetrating ionizing radiation. Damage caused by radiation absorption in Areas I, II, and III may be alleviated by appropriate medical treatment.

In this study therefore, the concern is solely to minimize radiation exposures to levels which will not result in acute disease symptoms. The increased probability for late effects are an accepted penalty in return for the success of early missions.

BIOLOGICAL RECOVERY AND RESIDUAL INJURY FROM IONIZING RADIATIONS

Man's capacity to absorb a given dose of ionizing radiations without manifesting either disease symptoms or causing fatality is depending on the capability of biological systems for repair of sustained injury. Recent theoretical considerations presume that recovery of a constant fraction of the injury remaining per given unit time occurs, except for that amount which was injured irreversibly. Blair[3] formulated an exponential equation for this occurrence and a modification derived by Davidson[5] is presented below:

$$D_e = D_o \,[f + (1 - f)e^{-\beta t}]$$

Where D_e is the effective dose in rads, D_o is the physically measured total dose, f is the non-recoverable fraction of injury and β is the recovery constant.

The theory as now formulated depends on two unknown quantities that must be estimated: the irreparable fraction of the injury (f), and the recovery rate (β). A number of animal experiments conducted within the last few years[6,7] seem to indicate a residual injury for the total animal system of approximately 10 per cent. For specific organs this may vary. For example Baum[1] computed a 20 per cent non-reparable injury for the erythropoietic system. However, when considering total animal systems such as man we must at present assume a best estimate for $f = 10$ per cent. Observations from animal experiments permit us to derive analytically best estimates for recovery half-lives which are definitely related to initial radiation exposure and correlated to injury. Davidson[5] has computed recovery half-lives for various animals, which are listed in Table I.

β=0.0277. With this value for β and with that obtained for f above, we are now able to construct the recovery curve as seen in Figure 3.

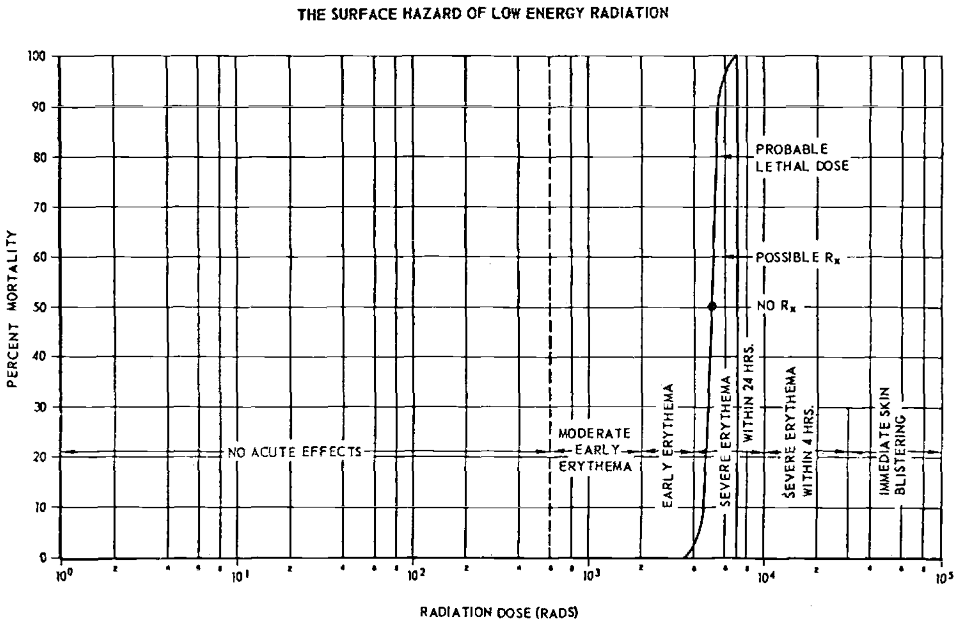

Fig. 2. Injuries to the skin due to absorption of low energy ionizing radiation.

TABLE I. ESTIMATED RECOVERY HALF-LIVES FOR VARIOUS ANIMALS

Animal	Recovery Half-Life (days)
Mouse	3 - 8
Rat	6 - 9
Dog	14 - 18
Burro	20 - 28
Man	25 - 35

The data for the first four animals in Table I have been obtained from experimental studies. It appears that the recovery half-life is related possibly to body weight of the species, but perhaps also to such parameters as life expectancy, basal metabolic rate or to the survival rate of radio-sensitive cells.[5] This permits an extrapolation for man, which should be somewhat higher than that for the burro.

Since recovery half-lives bear a simple relation $\left\{\frac{0.69}{\beta}\right\}$ to recovery rate, the latter may be easily computed from it. Assuming a best estimate half life of recovery of 25 days for man, then

PROPOSED PERMISSIBLE RADIATION EXPOSURE DOSE FOR SPACE PILOTS EXPECTED TO PARTICIPATE IN A NUMBER OF MISSIONS

From the previous discussion it may be derived that all permissible exposures for early space missions must be below the level which might incapacitate space pilots. It appears then that space ships must be shielded so that the probability will be large that exposure levels within them will never exceed 100 rads. Figure 3 shows the computed recovery curve for humans exposed to either 100 or 50 rads. After an initial exposure to 100 rads, a space pilot would probably need a rest period of 120 days before he should participate in a new mission with probability of radiation exposure. For example, second exposures of 100 rads 30 or 60 days after the initial 100 rads may produce incapacitating radiation sickness, which may result in an abort operation or even disaster. If the initial exposure were only 50 rads, the rest period may be shortened by perhaps 50 per cent and of course, residual injury is approximately one half.

The accumulated residual injury which presently is assumed to be 10 per cent of the original damage is, of course, another factor which will eventually determine the operational life span of astronauts. If it is additive as Blair[4] suggests, then ten exposures to 100 rads with at least 120 days intervals between exposures, would be the permissible limit. No further mission would be permitted thereafter. As a matter of fact it is questionable whether or not, space pilot after four or five exposures to 100 rads should be subjected to another mission with a probability of radiation exposure. The accumulated non-reparable injury in addition to the newly sustained injury, may very well produce overt disease symptoms.

It is quite possible that residual damage accumulates exponentially, and is a constant fraction of the remaining non-injured total mass of cells and tissues. Experimental results by Baum and Alpen[2] seem to support this contention. If this is the case, then this might permit astronauts one or possibly two additional space ventures.

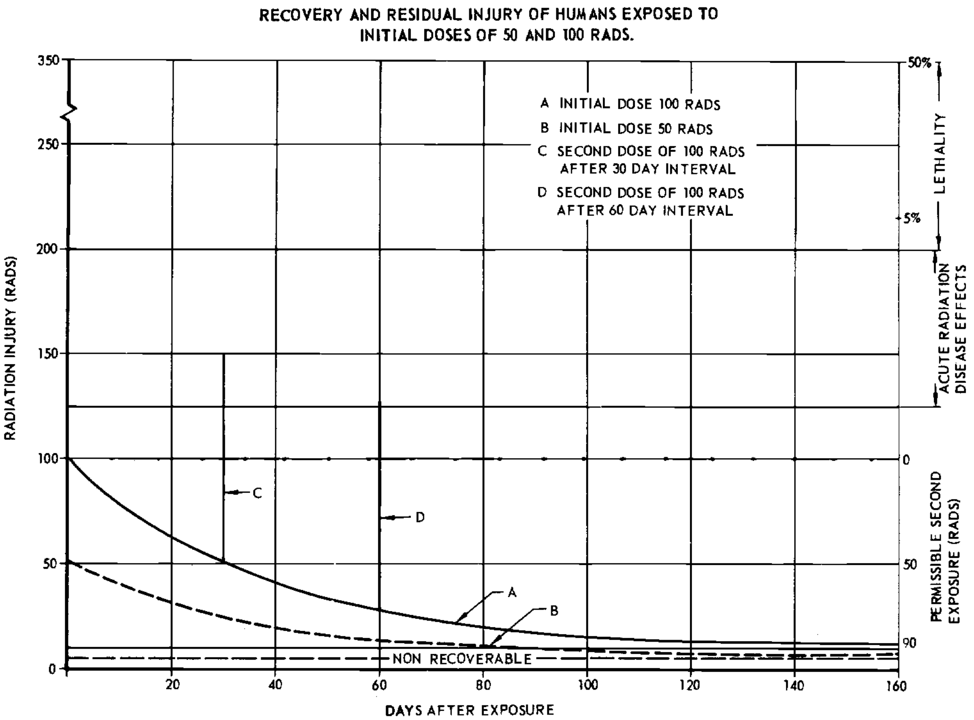

Fig. 3. Recovery and residual injury of humans exposed to initial doses of 50 and 100 rads.

It appears, then, that for early missions when thrust capabilities would not permit complete radiation shielding, enough shielding must be available to protect from any penetrating radiation in excess of 100 rads. The lower the initial exposures the longer will be the operational life of space pilots. Assuming a residual non-reparable injury of 10 per cent of that sustained prior to recovery, and when permitted at least 120 days of rest intervals between exposures of 100 rads, space pilots could probably be permitted five such exposures, thereafter the probability for incapacitating disease symptoms increases greatly at the next exposure. Obviously, this does not mean only five missions, since exposures to a dose of 100 rads should only occur at rare occasions in any given year. With luck, a space pilot may participate in a great number of missions over several years before he might encounter the number of solar storms which would subject him to the radiation exposures discussed above.

This analysis, however, should not be concluded without sounding a final warning. Any amount of radiation exposure may be considered as harmful. While radiation exposures may be one of the penalties astronauts may desire to pay in return for the accomplishment of historic tasks, the ultimate goal for future space travel must be complete shielding from all penetrating ionizing radiations.

SUMMARY

The present study represents an analysis of maximum permissible radiation exposures to highly radiosensitive organs of man for early exploratory missions. It is proposed that shielding should be designed so that a high probability exists that space pilot should not be subjected to penetrating ionizing radiations in excess to 100 rads. It appears that if astronauts are given at least 120 day rest periods for biological recovery between missions where potential exposures to 100 rads are a probability, they may absorb about four to five such radiation doses without facing biomedical incapacitations which could endanger a given mission. Based on the number of predictable solar storms which could create such proton energies in any year, it appears that by chance alone space pilots should participate in many early ventures, before the maximum permissible number of radiation absorptions has occurred.

REFERENCES

1. BAUM, S. J.: Erythropoietic recovery and residual injury in rats exposed repeatedly to x-rays. *Am. J. Physiol.*, 200:155, 1961.
2. BAUM, S. J. and ALPEN, E. L.: Residual injury induced in the erythropoietic system of the rat by periodic exposure to x-radiation. *Radiat. Res.*, 11:844, 1959.
3. BLAIR, HENRY A.: A Formulation of the Injury, Life Span, Dose Relations for Ionizing Radiations. University of Rochester (UR-206) Atomic Energy Project, Rochester, New York, May 13, 1952.
4. BLAIR, HENRY A.: Recovery from Radiation Injury in Mice and Its Effect on LD_{50} for Durations of Exposure up to Several Weeks. University of Rochester (UR-312) Atomic Energy Project, Rochester, New York, February 10, 1954.
5. DAVIDSON, HAROLD O.: Biological Effects of Whole-Body Gamma Radiation on Human Beings. Baltimore: Johns Hopkins Press. 1957.
6. KAPLAN, H. S. and BROWN, M. B.: Mortality of mice after total-body irradiation as influenced by alternations in total dose, fractionation, and periodicity of treatment. *J. Natl. Cancer Inst.*, 13:185, 1952.
7. KREBS, J. S., BRAUER, R. W. and KALBACH, H.: The Estimation of the Non-Recuperable Injury Caused by Ionizing Radiation. USNRDL-TR-226, April 18, 1958.