note technique

Problems of radiation in space*

W. SCHIMMERLING*

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Human space exploration in the 21^{st} century holds exciting prospects for the advancement of science and the expansion of our experience. Projected missions include an outpost on the Moon and a piloted mission to Mars. However, for space exploration to proceed, adequate protection of crew members must be ensured against the hazards presented by the harsh environment of space, in particular against the hazards of ionizing radiation. While much still remains to be learned in all aspects of radiobiology, major unresolved issues for human activities in space are :

– radiation protection against large fluxes of high energy protons from solar energetic particle (SEP) events,

– the possible existence of new or qualitatively different biological effects, either not seen, or not seen at comparable radiation levels, for conventional (low-LET) radiation such as X-rays or γ-rays, and

– the uncertainties associated with predicting biological effects, even when these are known, based on extrapolations from low-LET data and sparse high-LET data.

The space radiation environment consists of protons and electrons trapped in the earth magnetic field, protons (and some heavier particles) emitted in the course of solar disturbances (SEP), and protons and the energetic nuclei of other elements (HZE particles) that constitute galactic cosmic rays (GCR). The HZE particles, although contributing less than 1 % of the GCR flux, make a much larger contribution to the dose due to their higher rate of energy deposition, and may be biologically the most significant component of GCR radiation.

Energies of the GCR particles range from less than a few MeV per nucleon to over 10,000 MeV per nucleon. According to calculations by G. Badhwar at the NASA Johnson space center, approximately half the dose equivalent in free space is due to GCR particles with energies above 1 GeV/nucleon (although this proportion depends on shielding thickness). L. Townsend, at the NASA Langley research center, has calculated that 7 components, nuclei of H, He, C, O, Mg, Si, and Fe, contri-

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** Universities Space Research Association, 409 Third St SW, Suite 330, Washington, D.C. 20024, USA.

bute more than 70 % of the dose equivalent due to GCR, again depending on shielding thickness. However, with increasing shielding thickness their contribution increases. Of these components, the most important are protons and iron nuclei. Calculations by J.W. Wilson, also at NASA/Langley, indicate that GCR constitute a significant component of cell transformation, even in low earth orbit (LEO) radiation fields. The LET spectrum can extend to ~ 1000 keV/μm, leading to large quality factors assigned for the purposes of radiation protection.

The scientific knowledge required to predict radiation risk in space from first principles is not currently available. Therefore, predictions of radiation risk in space need to be derived from models based on empirical data. The data need to be sufficiently detailed to minimize interpolation errors, and they need to cover a wide range in order to minimize the errors introduced by extrapolation of measured quantities to the space environment.

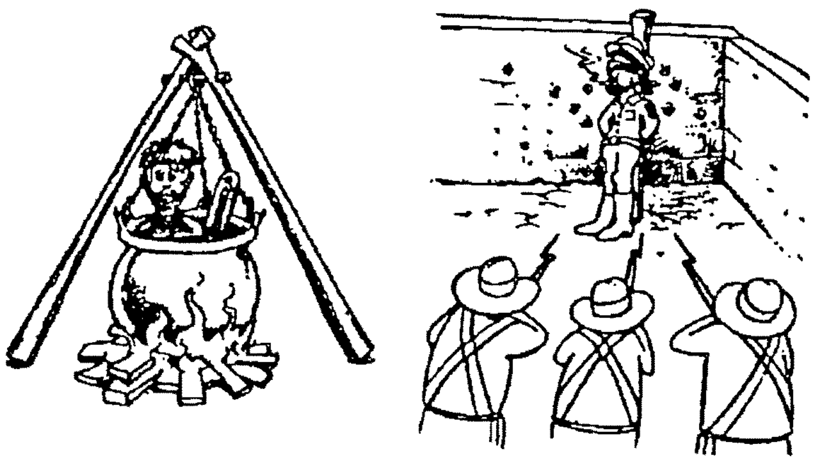
A schematic description of the rationale for the overall approach to the program goals is given in figure 1. Since the purpose of research is to assure the protection of humans in space, significant results of their exposure to radiation cannot be expected. Furthermore, it is generally more cost effective to perform scientific research on the ground. Direct ground-based data on radiation effects in humans are only available as a byproduct of medical treatment (*e.g.*, cancer therapy), of accidental exposures, and as the result of analyses of atomic bomb survivors. Therefore, the estimation of radiation effects on humans will, of necessity, be based on chains of inference, using the best judgment of the scientific community as to what links to accept or require in forging such chains.

What is radiation risk (effect and uncertainty) to humans in space ?
↘
What is radiation risk to humans on earth ?
↘
What is radiation risk for small mammals ?
↘
How does one extrapolate from mice to men ?
↘
Transformation, mutation, genomic instability,
oncogene activation, suppressor deletion,
carcinogenesis, DNA deletion size,
etc. *vs.* LET(?) in mammalian (?) cells.

Fig. 1. – Rationale for space radiation research.
Logique de recherche sur les rayonnements dans l'espace.

Mammals are the organisms most similar to humans, and it is logical to assume that investigations of biological effects of radiation on mammals are an important component in the necessary research. Small mammals afford the best statistical basis for such studies and have the added interest that a substantial data base exists for studies with conventional types of radiation. However, we currently lack the knowledge to make reliable extrapolations from animal studies in one species to another and, therefore, to human beings. For this reason, studies are required to elucidate the mechanisms of radiation action and their modification in intact tissues, organs and organisms.

The most important biological hazards associated with ionizing radiation particles are so-called "late effects", occurring during the remaining life span of the individual after exposure. Life threatening and life shortening effects, in particular cancer, are of greatest concern. Mutagenesis and tissue damage, including cataract formation, are also significant adverse health effects. Neurological and behavioral effects and their consequences for crew performance likewise need to be understood. The biological effects of exposure to radiation and, in particular, the resulting risk of cancer, depend on a multitude of factors. Among the most important are : the dose, the dose rate, the rate of energy deposition along a particle trajectory ("linear energy transfer" or LET), the age at exposure, the organ or organs irradiated, etc. The same dose, delivered by different types of radiation, does not always result in the same biological effect.



Low LET   High LET

Fig. 2. – The difference between low LET and high LET.
Différence entre faible et fort TLE.

A fanciful, but intuitive way to illustrate the different behavior of different types of radiation may be obtained from figure 2[(1)]. In previous ages of exploration, the radiation hazard may more likely have consisted of infrared radiation, originating in the fire under the pot to the left. As with X-rays, radiation in this situation could be reflected, absorbed, and transmitted by shielding. A thermometer is a highly effective dosimeter in this situation, because there is an equilibrium state and the temperature is approximately the same anywhere in the water bath. On the contrary, a thermometer would have no utility at all in the "high LET" cartoon on the

(1) I thank Mr. A. Joyce of the Lockheed Engineering and Science Corp. for translating my crude sketch into an artistic cartoon.

right. On the one hand, if it were placed in the hip pocket of the executed man, out of the way of the bullets, its indication of a zero dose would be irrelevant to the actual circumstances. On the other hand, if the thermometer were placed in the shirt pocket, in the way of the bullet, it might register a lethal "dose" but in reality save the life of the prisoner : equilibrium no longer holds.

A calculation of the energy required to raise the temperature of 1 kg of water from ambient to boiling requires a "dose" of approximately 250 000 Gy (J/kg). If this is regarded as an approximation to a "lethal" dose of heat radiation, the comparable energy dissipated by a bullet of 0.1 kg mass, exiting from a rifle with a muzzle velocity of 2 200 m/s, in an 80 kg body, is approximately 3 000 Gy. If one assumes that 10 bullets are required to ensure hitting the target, then the lethal dose would be 30 000 Gy, resulting in an RBE value of 8, not bad for such a comparison !

There are large uncertainties associated with every step in the complex chain of reasoning leading from evaluation of the radiation fields to prediction of any biological effects resulting from exposure to radiation in the course of lunar habitation or a trip to Mars. The spacecrafl designed by engineers must take these uncertainties into account in order to keep the radiation exposure within safe margins, which may be one or more standard deviations. As a consequence, additional shielding mass will be required, leading to increased costs associated with launching the extra mass into space. A diagram of this process is shown in figure 3.

Wilson *et al.* [1] have made a model calculation of the costs resulting from a one-standard deviation safety margin in the shielding required to limit radiation exposure to current LEO radiation limits, as a function of uncertainty in HZE dose-equivalent only. The results are shown in figure 4.

From such studies one can conclude that:

1. worst case calculations (based on order of magnitude estimates instead of detailed calculations) lead to unacceptable engineering designs ;

2. the most efficient way to reduce the costs of space exploration missions is by research leading to reductions in the uncertainty of risk predictions.

Neither of these conclusions should be surprising in itself. Given that the costs of launching materials into space are extraordinarily high, especially when these materials have to include human life support, the benefit of appropriate research by far outweighs the costs incurred by attempts to compensate for large uncertainties in risk prediction. It is clear that these uncertainties need to be reduced below the 200 % level in order to limit costs of shielding to a reasonable level. However, most subsequent reductions in uncertainty are likely to more than pay for themselves as well. ■

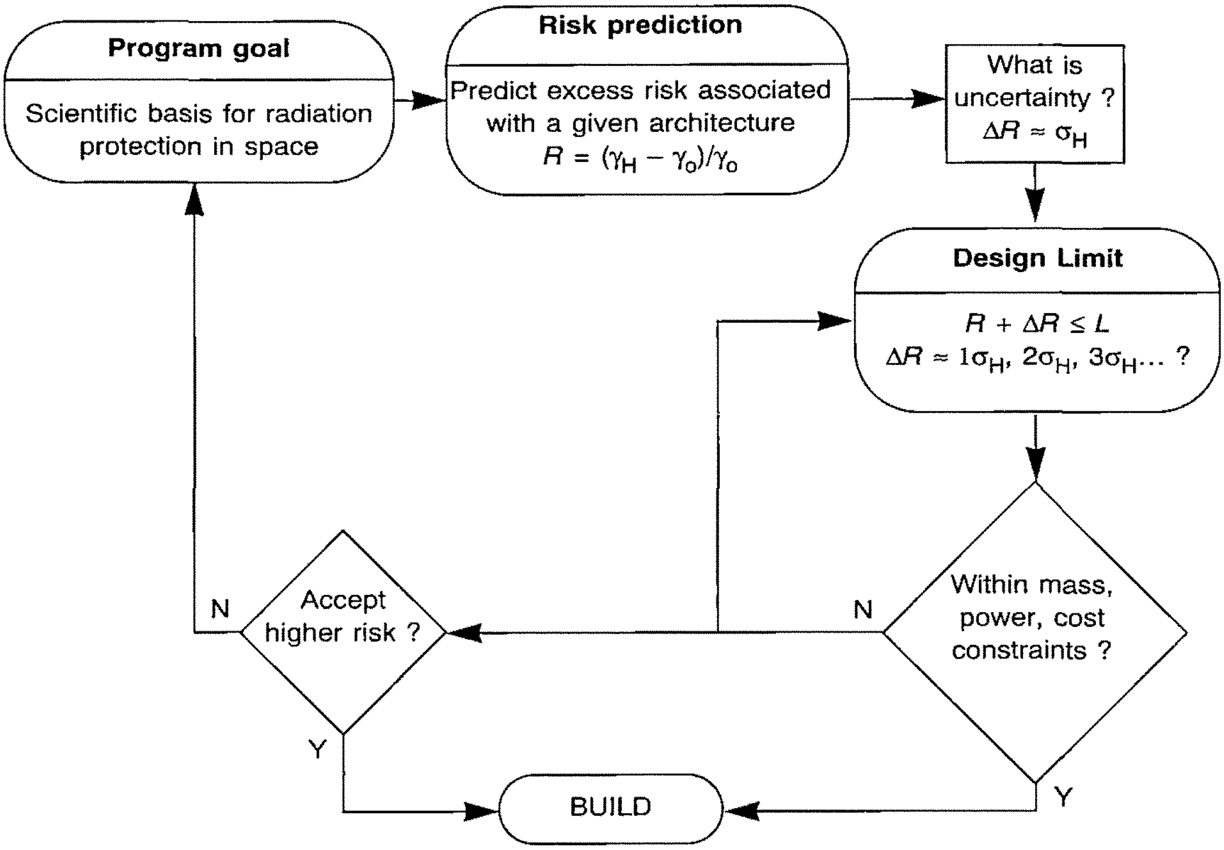


Fig. 3. – Uncertainties : the engineering perspective.
Les incertitudes vues sous l'angle de l'ingéniérie.

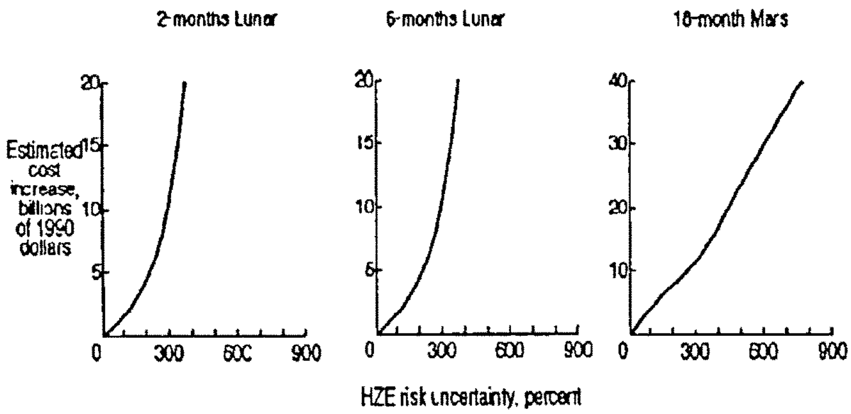


Fig. 4. – Estimated cost increase (in billions of 1990 dollars)
Accroissement du coût estimé des protections (en milliards de US $ 1990).

REFERENCES

[1] WILSON J.W., NEALY J.E., SCHIMMERLING W., CUCINOTTA F.A., WOODS J.S. Effects of biological uncertainty on deep space mission shield design (In preparation).