CHAPTER IV

Applications to Space Flight Operation*

A. General Considerations

The National Committee on Radiation Protection [NCRP (2)] and International Commission on Radiological Protection [ICRP (280)] have recommended protection standards for exposure to ionizing radiations. These recommendations were proposed to ensure radiological safety both for the occupationally exposed and for the general population and were predicated on the basic assumptions that radiation was the primary risk, the number of people exposed would be large, and the sources of exposure would be controllable. In order to cope with the objective of large-scale radiation safety, the concept of the "permissible dose" was established. The permissible dose for the individual was defined as "that dose accumulated over a long period of time or resulting from a single exposure which, in the light of present knowledge, carries negligible probability of severe somatic or genetic injuries; . . ."[280]

The Federal Radiation Council,[1] recognizing the inherent inflexibility of the permissible dose concept and the restrictions imposed by the basic assumptions of the NCRP, has officially authorized less restrictive measures by introducing the radiation protection guide (RPG). The RPG is defined as ". . . the radiation dose which should not be exceeded without careful consideration of the reasons for doing so . . ." In addition the Council states that ". . . there can be no single permissible or acceptable level of exposure, without regard to the reasons for permitting the exposure," and "there can, of course, be quite different numerical values for the RPG, depending upon the circumstances." Thus, space operations are not bound by the Federal Radiation Council to a specific set of "permissible dose" values or to the recommended RPG but are obligated only to choose acceptable radiation exposure limits after careful evaluation of potential risk versus gain. The objectives of space radiation protection are clearly to avoid unacceptable risk to the flight crew and jeopardy of the mission. The choice, however, of protection guides that are too restrictive may, through interaction with other safety features of the spacecraft and the mission, defeat both of these objectives. Manned space flight is a new occupation entirely different from those for which existing radiation protection standards were established, and a new approach not inflexibly prejudiced by current occupational values is required. The following seem to be valid reasons to justify a realistic review of the radiation hazards and problems of manned space flight and the establishment of new and independent radiation protection criteria for space flight crews:

(a) The radiation hazard is only one of many recognized and accepted serious potential hazards that could jeopardize the success of any space mission.

(b) The population at risk is extremely small and voluntary (the latter factor does not imply that a justification for relaxing control exists, but that part of the burden of control is automatically apportioned to any volunteer).

(c) The exact time, rate, duration, radiation quality, and frequency of exposure are largely unpredictable and uncontrollable, requiring inclusion of on-board protective means in the form of shielding. Since this can create an undesirable weight penalty, the radiation risks must be balanced against those invoked by the equipment capability traded for shielding weight.

(d) Each flight may have a different profile and a different goal and, therefore, a different risk versus benefit evaluation.

B. Space Radiation Protection Guide

A few attempts have been made to specify exposure limits or guides for manned space flight operations. Despite the clear differences in requirements for radiation safety between employees in conventional industries involving radiation risk and astronauts, the ICRP/NCRP recommendations were used as a basis on which to establish dose values to be used as design criteria for the Apollo mission.[281] As a basis for shielding considerations, values were specified for acceptable career, yearly average, and emergency maximum acute dose limits at the average effective depths of the most critical or limiting tissues or regions of the body. Career and yearly average dose limits were derived on the assumption that the acceptable career dose (in rems) is the same for space crews as for any other occupationally exposed group, although their active career was assumed to be about 5 years compared to 50 years for other occupations. The career dose (in rems) was divided by what seemed to be a reasonable QF and by 5 to obtain an acceptable yearly average dose in rads. The average yearly dose, of course, is a factor of 10 higher than recommended for conventional industrial careers of 50 years anticipated duration. Maximum emergency acute exposure limits were defined as the limits beyond which there would be an unacceptable probability of permanent injury, death, or incapacitation to the extent that the crew might be unable to execute the mission. The values were chosen on the basis of observed or surmised clinical effects of acute radiation exposure in relation to dose. This time-scale

*A major portion of this section was presented in a paper by Grahn and Langham[279] before the Second Symposium on Protection against Radiation Hazards in Space, Gatlinburg, Tennessee (October 12-14, 1964).

compression and attention to observed acute effects produced a set of exposure limits that in some respects were reasonable but somewhat arbitrary and devoid of flexibility. Another set of acceptable exposure limits has been proposed which is not arbitrarily related to the NCRP/ICRP recommendations[282] but is subject also to the lack of flexibility inherent in any specific set of values which cannot take into consideration variability of conditions and potential risk versus gain considerations.

Schaefer[222,283] proposed space radiation tolerance criteria on the basis of the equivalent residual dose concept. He arbitrarily chose a maximum permissible net injury level of 50 and 80 rems, and assuming a repair half-time of 25 days and an irreparable component of 10[283] and 22[222] per cent calculated the acceptable grand total accumulated dose as a function of exposure or mission time. Using the Blair hypothesis, a recovery half-time of 25 days, and an irreparable component of 10 per cent, Baum[223] proposed a maximum acute exposure limit of 100 rems and a career limit of 5 such exposures with a minimum recovery period 120 days between missions. Odland and Michaelson[224] have suggested also the Blair hypothesis as an approach to the prediction of crew response to space radiation exposure.

Rather than try to develop general radiation protection guides specifying fixed acceptable values which cannot provide the flexibility required by variability of conditions and potential risk versus gain considerations, it seems more reasonable to specify radiation response criteria for hazards evaluation to be used in developing maximum acceptable risk values based on the nature and requirements of each individual mission. Wherever possible, the response criteria should be considered as probabilistic functions of dose. It is recommended that radiation risk be evaluated in the following categories, listed in the order of potential importance:

1. Immediate or early radiation sequelae (within a few hours or a few weeks) at any time during flight.
2. Progressive radiation sequelae or semi-acute hematopoietic deterioration during long flight periods.
3. Probabilities of late or delayed sequelae as they may necessitate intervention in planned flight series and astronaut careers.

Evaluation of the hazards comprising these categories may be accomplished, within the limitations of the data, from the dose-response relationships given in Chapter III taking into consideration, where possible, the information on modifying factors discussed in section III.E.

1. IMMEDIATE OR EARLY RADIATION SEQUELAE

This category consists of those responses to acute or mixed acute and chronic radiation exposure that will neccesitate emergency or abort decisions. Depending upon the penetrating quality, total dose, and intensity of exposure, the limiting systemic and/or tissue responses are:

a. Acute Gastrointestinal or Prodromal Symptomatology (i.e., Nausea, Vomiting, Diarrhea)

Insofar as possible, the dose-response relationship for the prodromal reaction is shown in Figure III-4. Prodromal symptoms (discussed in section III.B.2.a) may appear with a probability of about 5 per cent within 1 to 5 hours after an acute dose of 75 to 100 rems at the midline of the trunk.

b. Acute Hematopoietic Symptomatology (i.e., Thrombocytopenia, Leukopenia, Hemorrhage, Intercurrent Infection)

These symptoms (discussed in section III.B.2.b) will appear within a few days to 3 weeks and can reach a clinically aggravating level at doses of 150 to 200 rems or more at the average effective depth of the bone marrow delivered over a period of several days.

c. Erythema and Skin Blistering

Under certain circumstances, such as extravehicular operations, high intensity surface exposure with little deep tissue dosage may occur. The nature and dynamic dependency of early skin response on time-intensity-dose factors are discussed in earlier sections (III.B.2.c[1] and III.E.3.c). Mild erythema will appear within a few hours to days following an acute dose of 650 to 700 rems at the depth of the basal layers of the skin. Severe damage will occur at doses of 1800 to 2000 rems and perhaps even death at these doses if exposure involves a major fraction of the total skin area. Due to the restrictions and abrasive contacts of the space suit, even a partial-body moderate erythema could become extremely uncomfortable and somewhat incapacitating.

d. Degradation of General Operational Skills through Direct and Indirect Physiologic and Neurologic Reactions

The significance of possible radiation-induced neurologic and behavioral responses (discussed in section III.B.2.e) cannot be evaluated at the present time. Apathy, lassitude, fatigability, etc., however, are definite responses to radiation exposure which could reduce the performance capacity of a crew. The induction of any systemic radiation response may be expected to induce secondary effects that may influence performance level.

Maximum acceptable risk levels for these end points should be defined for each individual mission. The lowest limit will be first determinant, but this will be a function of depth-dose variation, total dose, and dose rate. For example, a high dose rate, whole-body exposure to a penetrating radiation will undoubtedly cause the dose for the prodromal response to be determinant. A more protracted exposure will bring hematopoietic injury into the determining position,

and when moderate to high doses of very low energy radiations prevail under certain low shielding exposure conditions skin injury will be limiting.

2. PROGRESSIVE RADIATION SEQUELAE

This risk category recognizes that most exposures will be at low levels where no early manifestations will occur, but continued or periodic exposures can lead to a progressive emergency of principally hematopoietic injury expressed as a decrementation of performance or general well-being necessary to maintain normal flight operations. This category also encompasses one of the most difficult areas for the prediction of biological response (i.e., the situation following fractionated and protracted exposure).

Radiation injury has a comparatively slow time-course of expression, and its manifestations will progressively emerge, then subside. Expression and recovery are concurrent. When the exposure is essentially continuous but at a low daily rate (perhaps 2 r/day or less for man), injury and recovery will probably equilibrate and a steady state will be maintained for long periods. Such observations have been made in experimental animal populations[284] and certainly would occur in man, but there are not yet sufficient data available to establish the kinetics of injury and recovery with any degree of confidence.

The Blair hypothesis,[206] which is the basis of the equivalent residual dose (ERD) concept discussed in detail in section III.E.3.b, is the most widely known attempt to deal with progressive injury from radiation exposure. Unfortunately, the assumptions and constants employed in the equivalent residual dose calculations have not been validated in man and are in conflict with a considerable body of present radiobiological data. The ERD concept is not based upon a correlation of physiological or cellular injury with lethality and, therefore, it cannot determine in any specific way a dose accumulation that can be related to an acute response end point.

Prediction of man's response is difficult enough when a regular pattern of protracted or fractionated exposure obtains, but when the erratic pattern of exposure likely to occur under most projected flight profiles is considered, the situation becomes virtually impossible on the basis of present knowledge. The prodromal symptoms and acute skin response will certainly benefit from dose protraction. The practical question related to progressive radiation debilitation is: To what extent will the hematopoietic system benefit and what are the significant time factors? The answer to this question is largely unknown at present. Nevertheless, equivalent residual dose calculations may be useful if limited to dose levels which are sufficiently small to have a low probability of significantly damaging the body's repair mechanisms. It is felt that potential response to small fractionated doses of less than 25 to 50 rems may be evaluated by allowing for recovery during exposure-free or very low-level (less than 2 rems/day) continuous exposure intervals of at least several weeks to several months duration. No particular recovery constant is recommended for the ERD calculations except that it should be no greater than 2.5 per cent per day and perhaps lower if it is to integrate all recovery processes acting over the first several months to a year. For higher daily doses and fractionated exposures, evaluation on the basis of simple unweighted dose accumulation would seem prudent. It is suggested, therefore, that a straight dose accumulation be used to evaluate potential acute and sub-acute hematopoietic response to fractionated exposures of about 50 rems or more per fraction and continuous exposures of greater than 2 rems/day.

3. LATE OR DELAYED RADIATION SEQUELAE

Late or delayed manifestations of radiation exposure generally appear to be of secondary importance in the evaluation of the hazards of manned space flight. This should be the case for the near future. The secondary role of delayed responses is in sharp contrast to their role in evaluation of occupational hazards. In the latter case, late effects are paramount.

Although the reasons for relegation of late effects to a secondary role are several, the most quantitative argument is in the matter of population size. In the next several years, the astronaut population may be no more than a hundred or so; the occupational group may be 200,000 or more. Late manifestations of radiation damage are measured in probabilistic and actuarial statistical terms and consist of an increase in an age-cause specific death rate, a reduction of the after-expectation of life, an increase in the sporadic incidence of cataracts, leukemia, and other malignant diseases, and in detrimental mutations. The end points are not identifiable with an individual but are entities of the population. Some reasonably acceptable dose-probability relationships for various delayed somatic effects are presented in section III.C, all of which are based on total accumulated dose.

It goes without saying that accurate records of the radiation history should be kept on all flight personnel. It would seem important to be able to select freely from among the experienced personnel those crews that best meet specified mission requirements. This may entail periodic or repeated use of some astronauts and the possibility of dose build-up to an undesirable level as far as the individual's after-expectations are concerned.

Long duration missions may be jeopardized also if critical crew members should begin to develop manifestations of chronic injury when turn-around time may be many months. For this reason, the evaluation of late effects of radiation damage will progressively increase in its importance in the benefit-risk analysis. It is felt, however, that these end points should be given little weight in the present era of experimental manned space flights.

Genetic manifestations of radiation exposure always receive a little extra attention. This is justifiable in case of the population-at-large under risk of exposure

from fallout radiation or unnecessary medical or dental radiation sources. The gene pool of large populations is sufficient to cause the predictions for even very low probability mutation events to reach values of real concern. Based on statistical reasoning, however, the genetic hazards associated with manned space flight must be considered extremely small. This should not be misconstrued as meaning that the genetic damage should be of no concern to the individual exposed. Certain probability statements can be made concerning the individual, but the acceptance or rejection of these probabilities is a personal matter.

The next logical concern is the question of a "career dose." If it is accepted that career limits are a necessity, then some set of specific values must be established as acceptable integral doses for various time periods. It is doubtful that present knowledge is adequate to assure this can be done now without being either too restrictive or not restrictive enough. Although one of the authors has previously discussed such limits,[282] it is generally felt premature to dwell on the problem of career dosage here, if for no other reason than to avoid setting unrealistic figures for single missions and for annual exposure increments. These are almost automatically derived when a career dose is established.

One additional uncertainty needs to be noted. This concerns the problem area of combined stress. There is at present no information regarding the interaction of weightlessness, radiation, and other factors such as the subtle effects that may accrue from prolonged periods of low physical activity and high demand for exceptional operating proficiency. What influence, if any, concurrent physiological and psychological stresses may have upon the expression of radiation damage cannot be ascertained. Since any interaction is liable to influence the response in a negative way, an element of conservatism should be kept in all determinations.

In the meantime, flights will be programmed for longer periods and some limits will be sought for 6-month, 1-year, and 2-year flights. How should accumulating dose be weighted for prediction of early incapacitation, progressive incapacitation, and chronic injury? Some suggestions have been made in this discussion. In recapitulation, for early incapacitation, one will almost invariably be dealing with a single brief exposure and the estimated exposure dose at critical tissue levels will be determinant. For progressive debilitation, unweighted accumulated dose under certain exposure patterns may be used for hematopoietic end points, with the cutoff being the abort dose. For chronic injury, again a straightforward dose accumulation may be used.

C. Space Radiation Dosimetry

Radiation dosimetry is a highly specialized and rapidly developing field employing many different principles of dose measurement, depending on nature of the radiation, type of measurement and read-out required, dose range of interest, and other specific requirements. It is not the intent of this section to review the present state of dosimetry or the various types of dosimeters, their limitations, and applications. Rather, it is to consider in a very general way the requirements for on-board dosimetry in manned space flight missions.

The entirety of this report and the concept of radiation protection guides are predicated on the basic assumption that man's response to radiation exposure is a probabilistic function of dose. It is an obvious fact that attenuation of space radiation exposures to routine occupational levels by addition of shielding is impractical if not impossible during the next several years. It is a fact also that the sources of space radiation are uncontrollable and exact time, rate, duration, radiation quality, and frequency of exposure are, at present, largely unpredictable. Under these circumstances, operational decisions may have to be made regarding crew safety and mission outcome on the basis of measured dose and dose-response probability relationships or pre-established radiation protection guides for the particular mission. Decisions may have to be made also regarding crew selection for additional missions on the basis of career accumulated dose and the dose-actuarial risk relationships for late or delayed effects. At least two and probably three distinct dosimetry systems appear necessary to supply adequate information, depending upon whether or not extravehicular activity is contemplated; these are:

(a) A cabin monitoring system for continuous onboard and telemetry read-out of dose rate and accumulated dose.

(b) An individual personnel dosimetry system with sensors located on or in the body of each crew member but without provision for in-flight read-out.

(c) An extravehicular dose rate monitoring system.

The first system should provide adequate information to enable the astronaut and/or the mission commander, at any instant, to balance the accumulated dose against dose rate and remaining mission length so that the over-all radiation risk may be evaluated with respect to mission abort or continuation. The data must be sufficient, when related to information on dose-response probabilities, to allow such a judgment to be made on the basis of: (1) the probability of performance degradation or danger from immediate or early radiation sequelae; and (2) the probability of progressive radiation deterioration occurring during the mission.

The second system will be necessary to: (1) assess the accumulated dosage to each individual crew member (this will vary depending upon crew movement within a nonhomogenous vehicle and extravehicular activity) for the purpose of keeping career dose records to be used to evaluate the probability of late or delayed radiation sequelae; (2) serve as post mission check on other spacecraft systems; and (3) determine the dose received at various locations on and within the body.

The third system should be located outside the spacecraft and is a requirement for data collection and when outside activity is contemplated. It will provide a basis for determining the length of time the astronaut

can remain on the exterior before there is a probability of any serious consequences. To this end, the dose rate from the instrument should be read out independently of the first system. For the purpose of recording total dose, a provision should be made to superimpose the data from this system on the first system's display either directly or by manual feed-in. In the latter case, it will be necessary for the astronaut to keep time and dose rate records. This system should include a portable dose-rate measuring instrument, whenever there is a possibility of a long-range excursion from the spacecraft.

Since radiation response is a function of absorbed dose at the point of interest, all dosimetry systems should measure tissue dose or provide measurements amenable to conversion to tissue dose at the point of interest, regardless of type or quality of the incident radiations. Radiation response is also dependent on LET. As exposures will be to heterogeneous radiations for which the total dose is delivered partly by a low LET and partly by a high LET component, inclusion of an LET or energy spectrometer in the first dosimetry system perhaps should be considered.[285]

Combinations of various types of radiation sensors, such as tissue-equivalent ion chambers, fission foils, photographic emulsions, semi-conductor devices, and thermoluminescent detectors, should make possible the development of the required dosimetry systems.