NCRP REPORT No. 142

OPERATIONAL RADIATION SAFETY PROGRAM FOR ASTRONAUTS IN LOW-EARTH ORBIT: A BASIC FRAMEWORK

NCRP

National Council on Radiation Protection and Measurements

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Operational Radiation Safety Program for Astronauts in Low-Earth Orbit: A Basic Framework

Recommendations of the
NATIONAL COUNCIL ON RADIATION
PROTECTION AND MEASUREMENTS

Issued November 30, 2002

National Council on Radiation Protection and Measurements
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Library of Congress Cataloging-in-Publication Data

National Council on Radiation Protection and Measurements.
Operational radiation safety program for astronauts in low-earth orbit : a basic framework : recommendations of the National Council on Radiation Protection and Measurements.
p. cm. — (NCRP report ; no. 142)
"Issued November 2002."
Includes bibliographical references and index.
ISBN 0-929600-75-4
1. Extraterrestrial radiation—Safety measures. 2. Astronauts—Health and hygiene. 3. Space medicine. I. Title. II. Series
RA1151.R33 N38 2002
616.9′80214—dc21 2002037861

[For detailed information on the availability of NCRP publications see page 150.]

Preface

This Report was developed under the auspices of Scientific Committee 46, the National Council on Radiation Protection and Measurements (NCRP) program area committee concerned with operational safety. This Report addresses the operational radiation safety program for astronauts working in low-Earth orbit, with particular attention to the radiation dosimetry needed, the radiation exposure information that should be recorded, and ways to implement the radiation protection principle of "as low as reasonably achievable" for activities involving the Space Shuttle and the International Space Station. It is a companion document to NCRP Report No. 132, *Radiation Protection Guidance for Activities in Low-Earth Orbit*, published in December 2000, and provides advice on implementation of NCRP Report No. 132 guidance.

This work was performed at the request of the National Aeronautics and Space Administration (NASA) and NCRP gratefully acknowledges NASA's support. The Scientific Committee that prepared this Report also benefited from a series of briefings from NASA staff at the Committee's first meeting in December 1999 in Houston.

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The Council wishes to express its appreciation to the Committee members for the time and effort devoted to the preparation of this Report.

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Contents

1. Summary and Recommendations

Astronauts are living and working for extended periods in low-Earth orbit (LEO) during Space Shuttle missions and construction, maintenance and operation of the International Space Station (ISS). The radiation environment they encounter in space is complex, with unique high-LET (linear energy transfer) and high-energy components, as distinct from the predominately low-LET and low-energy radiation environments encountered by most radiation workers on Earth. The primary purpose of an operational radiation safety program for astronauts working in LEO is to assess and control the radiation exposure of individual astronauts commensurate with mission tasks and the prevailing radiation conditions in LEO.

1.1 Components of an Operational Radiation Safety Program

The main components of an operational radiation safety program designed to implement the principles of dose limitation and ALARA (as low as reasonably achievable) for astronauts working in LEO are:

- to facilitate actions, both in advance of a mission and in-flight, that respond to space radiation conditions or mission decisions that significantly affect the level of radiation exposure to the astronauts, and radiation protection decisions that significantly influence the conduct of the mission;
- to collect and record data to assess astronaut doses for individual mission and cumulative career records; and
- to identify, plan and carry out practical ALARA actions to avoid unnecessary levels of radiation exposure.

***Recommendation 1*: National Aeronautics and Space Administration (NASA) management should implement and maintain an effective radiation safety program with the following features: clear definition of the goals of the program, statement of the organization's commitment to the application**

of the ALARA principle, statement of management's commitment to provide adequate budgetary support for the program, and periodic review of the overall program performance.

***Recommendation 2*: NASA management should clearly assign responsibility for ensuring the translation of radiation protection strategies and instrumentation from design and development through engineering, preparation for flight, and use in orbit.**

1.2 Team Management in the Radiation Safety Program

Management of the radiation safety program in LEO is a team effort, involving the astronauts, the flight director, the flight surgeon, the radiation health officer (RHO), and the Space Radiation Analysis Group (SRAG). Typically, astronauts do not play an active role in decision making and policy regarding radiation protection issues. Instead, the flight director and flight surgeon direct their radiation protection actions, with the help of radiation experts. The current roles of these individuals are noted below.

Usually, one or two astronauts with medical backgrounds represent the U.S. Astronaut Office's position regarding radiation protection at the various meetings and committees. If radiation exposure is expected to be more than minimal, the affected astronauts may participate more actively concerning their particular flight.

The flight director is the final decision maker in the Mission Control Center with regard to all aspects of a mission, and the flight director relies heavily on the radiation team and flight surgeon when decisions regarding radiation protection issues need to be made.

The flight surgeon is responsible for the crew's health and safety during all aspects of flight, and briefs the crew pre- and postflight regarding radiation protection issues and personal radiation dose.

The RHO is involved in development and design of radiation protection strategies and provides recommendations to minimize crew exposures during mission planning and during space missions, tracks crew exposures against career limits, and provides risk interpretation for acute exposures.

SRAG consists of NASA radiation specialists who are responsible for promoting ALARA in development and design of radiation protection strategies and ensuring compliance with ALARA procedures. During a mission, SRAG provides an interface to update mission significant radiation events, particularly when transient events in

the space radiation environment produce a potential for high doses to the astronauts.

***Recommendation 3*: NASA's operational radiation safety program for LEO should have clearly defined responsibilities given to an individual or group to ensure overall implementation of the program. This individual or group may include individuals from those listed above, and/or members of NASA management who are able to work across all levels of operation to ensure radiation safety actions are considered for implementation.**

1.3 Sources of Radiation in Space

The predominant sources of radiation in LEO are galactic cosmic radiation (GCR) (high-energy protons, helium ions, and heavy ions of extra-solar origin); solar particle events (SPE) (primarily medium-energy protons of solar origin); the radiation belts outside Earth's atmosphere (high-energy protons and electrons trapped in Earth's magnetic field); and scattering from Earth's atmosphere (albedo neutrons, electrons and protons). There is a real potential that high transient radiation doses to astronauts will occur occasionally during construction and operation of ISS, particularly from SPEs and relativistic electrons from the outer radiation belt.

1.4 Dose Limits for Astronauts

The current recommended dose limits for astronauts in LEO were developed in NCRP Report No. 132 (NCRP, 2000a). The limits for bone marrow, lens of the eye, and skin are for protection against deterministic effects. The career limits are for protection against delayed stochastic effects and are based on a lifetime excess risk of cancer mortality of three percent.

The following formulations and terminology are used in this Report for the dose-limit quantities for space activities:

- The dose limits for the relevant organs or tissues for deterministic effects are expressed in terms of gray equivalent, where gray equivalent is the mean absorbed dose in an organ or tissue modified by a recommended value, for radiation protection purposes, of the relative biological effectiveness of a given particle type, as given in NCRP Report No. 132 (NCRP, 2000a). The

recommended values and dose limits for deterministic effects are given in Tables 2.2 and 2.3, respectively. A conventional notation $G_T = R_i D_T$ is proposed for gray equivalent and used in this Report. G_T is gray equivalent, R_i is the recommended value for relative biological effectiveness of a given particle type i, and D_T is the mean absorbed dose in an organ or tissue.

- The career limits for delayed stochastic effects are expressed in terms of effective dose (E), where:

$$E = \sum_T w_T H_T . \quad (1.1)$$

H_T is the equivalent dose and w_T is the tissue weighting factor. The career limits are given in Table 2.4 and are specified by gender and age.

- For the complex mixtures of high- and low-LET radiations experienced in LEO, the practice in the space radiation protection community is to obtain point values of absorbed dose (D) and dose equivalent (H) {using D and the quality factor relationship as a function of LET [$Q(L)$]}. The point quantities are then averaged over the organ or tissue of interest by means of computational models to obtain the organ dose equivalent (ICRU, 1993), which has been assigned the symbol $\overline{H}_T$ in this Report. This practice permits more complete consideration of the $Q(L)$ relationship for these complex radiation environments. The currently recommended $Q(L)$ relationship is given in NCRP Report No. 116 (NCRP, 1993) and is shown in Equation 2.5. For space radiations, NCRP Report No. 132 (NCRP, 2000a) adopted $\overline{H}_T$, for operational radiation protection purposes, as an acceptable approximation for H_T for stochastic effects.

***Recommendation 4*: For the operational radiation safety program in LEO, organ dose equivalent ($\overline{H}_T$) should be used as the approximation for equivalent dose (H_T).**

1.5 Sources of Exposure Included in the Dose Limits for Astronauts

***Recommendation 5*: The dose limits for astronauts should include the cumulative dose from space flight, the dose associated with mission-related aviation activities (excluding commercial flights), the dose from biomedical research conducted as part of the astronaut's mission duties, and any**

other occupational doses including any received prior to work as an astronaut.

The dose limits do not include normal background radiation on Earth or radiation dose received from diagnostic and therapeutic medical procedures conducted as part of the astronaut's overall health care. In addition, previous medical radiation doses, from diagnostic and therapeutic medical procedures, are assumed to have provided the individual a greater benefit than the risk associated with the doses and should not be used in determining qualification for future occupational exposure.

1.6 Types of Radiation to be Assessed

The radiation environment external to a spacecraft in LEO consists of electrons, positrons, neutrons, protons and heavier nuclei [up to particle charge (Z) = 92]. Energies range from a few electron volts for trapped electrons and albedo neutrons to in excess of 10^{14} MeV for GCR ions. Most of the electrons will not penetrate the wall of the spacecraft, but could penetrate the space suits worn during extravehicular activity (EVA), resulting in doses to the skin and eyes. Nuclear interactions of neutrons, protons and heavier nuclei with spacecraft, space suits, Earth's atmosphere, and the human body produce secondary particles, which add to the radiation field. Radiation monitoring strategies vary according to particle charge, particle type, energy, and measurement location. The environment can be classified according to particle types and energies and where the measurements are to be made (*i.e.*, outside the spacecraft, inside the spacecraft, and inside EVA suits), as listed below (see also Table 4.1):

- trapped electrons—outside spacecraft and inside EVA suits
- reentrant and splash albedo electrons—outside and inside spacecraft, and inside EVA suits
- trapped protons (<10 MeV)—do not penetrate spacecraft or EVA suits
- protons and light nuclear particles (>10 MeV)—outside and inside spacecraft, and inside EVA suits
- GCR ions and secondary charged fragments—outside and inside spacecraft, and inside EVA suits
- charged-particle fragments—inside spacecraft and inside EVA suits
- neutrons—outside and inside spacecraft, and inside EVA suits

The relative contributions from each component (including the secondary radiation) at each location will vary according to several factors, including the mass distribution inside the spacecraft, the EVA suit design and materials, and the site of interest within the human body.

1.7 Approach to Dose Assessment for Astronauts

***Recommendation 6*: Dose assessment for astronauts should utilize a combination of radiation transport calculations and measurements as illustrated in Figure 5.1. The main features of the approach should include sequential assessment of the radiation environment at the exterior surface of the spacecraft, the interior radiation environments in the spacecraft and EVA suits, and the transmission of radiation to internal organs or tissues in order to estimate the dose-limit quantities. The radiation transport calculations are not intended to be a substitute for measured data, but are designed to augment the measurements such that the combination of measurements and calculations should provide an estimate of the dose-limit quantities in Table 2.1 to within a factor of 1.5 at the 95 percent confidence level.**

Environmental models for GCR (and the associated albedo neutrons), trapped radiations, and SPEs are used to represent the exterior radiation field in LEO. External measurements can be made outside the spacecraft to allow correction to the models to reduce uncertainties.

Shielding models for the Space Shuttle, ISS, and EVA suits allow evaluation of the radiation environment to which the astronaut is exposed. Except for the absolute intensity of the trapped radiation or a SPE, the interior radiation environment can be evaluated with high-speed computational models. The interior radiation environments of the Space Shuttle and ISS can be monitored with various instruments and the measurements can be used to adjust the estimate of the trapped-particle intensity, reduce the uncertainty in the model estimates, evaluate transmission factors, and evaluate calculated dosimetric quantities. Personal dosimeters can provide estimates of absorbed dose at points on the surface of the astronaut's body.

The evaluation of organ or tissue doses for astronauts can be performed with computerized male and female anthropomorphic models. The models allow the evaluation of the relationships between

absorbed dose (D) and dose equivalent (H) at points on the surface of the body and the required quantities in deeper-lying organs [*i.e.*, mean absorbed dose in an organ or tissue (D_T) and organ dose equivalent ($\overline{H}_T$), the surrogate for equivalent dose (H_T)] that are needed to obtain the dose-limit quantities effective dose (E) and gray equivalent (G_T).

In addition, occupancy factors keyed to individual astronaut activity can be used to estimate exposures from the personal dosimeter measurements. This is especially true during EVA where large fluctuations in the trapped electron environment or SPEs could occur.

1.8 Operational Radiation Monitoring

***Recommendation 7*: Operational radiation monitoring consisting of area monitors and personal dosimeters should provide measured data of sufficient accuracy:**

- **for determination of field quantities and organ or tissue doses to be used for normalizing radiation transport calculations**
- **for dose assessment and record keeping purposes**
- **for real-time or near real-time estimates of dose rates for purposes of immediate dose management or ALARA**

1.8.1 *Area Monitoring*

***Recommendation 8*: Tissue equivalent proportional counters (TEPC) should be utilized during manned space flight for real-time measurements of absorbed dose and absorbed dose rate, and estimates of quality factor and dose equivalent to a small mass of tissue.**

A TEPC is an active detector that is designed to measure energy deposition in volumes of tissue comparable to the dimensions of the nuclei of mammalian cells. Data are recorded on an event-by-event basis such that one can obtain a distribution of biologically relevant energy deposition events. Its tissue equivalence and large dynamic range make it sensitive to photons, neutrons and charged particles from electrons and protons to heavy ions.

When the data are integrated over the complete distribution of lineal energy (y), TEPCs can generate absorbed dose (D) and absorbed dose rate ($\dot{D}$). The distribution of energy deposition events depends on characteristics of the radiation field and the response of

the detector, and can serve as a test for radiation transport models or to obtain an approximation to the quality factor (Q) for protons and heavier particles. This detector provides a reliable estimate of D from protons through high atomic number, high-energy (HZE) particles as well as photons, electrons and neutrons. Although the data in terms of y are not a direct replicate of the distributions of fluence [$\Phi(L)$] or absorbed dose [$D(L)$] as a function of LET (L), average values of y, in particular dose-averaged y, are numerically similar to L. Data from a TEPC can be displayed continuously and stored for later transmission to the Mission Control Center.

***Recommendation 9*: Solid-state detectors should be utilized during manned space flight for real-time measurements of LET distributions both inside and outside of the spacecraft.**

Solid-state detectors record the energy deposited by a charged particle. The ratio of the deposited energy to the thickness of the detector yields the approximate LET for the incident particle. Thus a single detector can provide data that yield absorbed dose (D) and absorbed dose rate ($\dot{D}$) for protons and heavier charged particles. It can be fabricated into a compact detector for use as portable area monitor or personal dose-rate meter with on-demand readout. Several of these detectors can be combined to point in different directions to provide a more complete description of the radiation field either outside or inside of the spacecraft.

***Recommendation 10*: An active detector sensitive to electrons should be installed outside of the spacecraft to serve as a monitor for fluctuations in the electron component of the space radiation environment, which can change by many orders of magnitude during and following an SPE due to short-term perturbations of the geomagnetic field.**

The fluctuations of the electron component could be of concern during an EVA, since electrons above a few hundred kiloelectron volts can penetrate the space suits. Such a monitor could be a simple ionization chamber with a wall thickness sufficient to attenuate very low-energy electrons but thin enough to record electrons that could penetrate a space suit.

1.8.2 *Personal Dosimetry*

***Recommendation 11*: A measurement package consisting of a thermoluminescent dosimeter (TLD) or optically stimulated**

luminescence dosimeter (OSLD) for measurement of the low-LET component, and a stack of plastic nuclear track detectors (PNTD) to determine the high-LET component should be used for passive personal dosimetry in the complex radiation field experienced in space.

LiF:Mg,Cu,P (lithium fluoride, doped with magnesium, copper and phosphorus) would appear to be an attractive TLD material. Alternatively, Al_2O_3:C (aluminum oxide, doped with carbon) is the best currently available OSLD material. To measure the dose equivalent (H) from the high-LET components, polyallyl diglycol carbonate [PADC/CR-39® (trade name CR-39, PPG Industries, Inc., Pittsburgh, Pennsylvania)] is the PNTD material proposed. Such devices have been used as part of the area monitoring or personal dosimeter packages on the Space Shuttle, but are not currently planned for ISS. It is recommended that they be used as personal dosimeters on both vehicles. CaF_2:Tm (calcium fluoride, doped with thulium) [*e.g.*, TLD-300® (Bicron, Saint-Gobain Industries, Cleveland, Ohio)] could also be used as an adjunct personal dosimeter to provide additional information to normalize radiation transport models, but not for quantitative determination of dose quantities.

With these detection elements in a passive personal dosimeter package, H at a point in adjacent tissue is then obtained by using a combination of TLDs (or OSLDs) and PNTDs, as described in Section 6.3. In this recommendation, TLDs (or OSLDs) are used to measure D in the low-LET region ($L < 10$ keV μm^{-1}) for which $Q = 1$. It is further recommended that D in the high-LET region ($L \geq 10$ keV μm^{-1}) be monitored using PNTDs. In this region Q is dependent on L. Correction may be needed for any overlap of the two responses so that intermediate LET components are not double-counted.

Verification of LET-dependence of the TLD response of LiF:Mg,Cu,P and of the OSLD response of Al_2O_3:C will be required. Until such time as these data are available, LiF:Mg,Ti-based dosimeters [*e.g.*, TLD-100® or TLD-700® (Bicron, Saint-Gobain Industries, Cleveland, Ohio)] may still be used, along with PNTDs, in order to provide LET data suitable for correcting the TLD dose response for the $L \geq 10$ keV μm^{-1} component, and for estimating H for this component from the PNTD results. If PNTDs cannot be used, a different, less desirable approach has to be adopted using TLDs and data from a TEPC or particle spectrometer, as described in Section 6.3.4.2.

For purposes of active personal dosimetry, a thick silicon detector may be able to provide an approximation to D, $\dot{D}$, and $D(L)$ for

protons and heavier particles. These have been designed in a sufficiently compact configuration to be worn by the astronauts and can be read on demand. In the case of currently available active personal electronic dosimeters, most are used routinely to measure low-LET radiation and have not been characterized for the types and energies of particles comprising the fields in spacecraft. Such dosimeters, when well characterized, may perform a useful role. Future considerations for active electronic personal dosimeters are noted in Section 6.3.2.3.

In those cases where active personal dosimeters are not used, onboard systems for analysis of passive personal dosimeters may be required, especially on long-duration ISS flights. Onboard systems for readout of TLDs and OSLDs are certainly possible. However, onboard readout of PNTDs is not feasible. Therefore, onboard readout of passive dosimeters will provide only part of the dose record (for low-LET) and development of such systems should only be considered if active personal dosimetry is unavailable.

The potential for developing a set of conversion coefficients that directly relate H obtained with TLDs and PNTDs at the surface to E for the space radiation environment, similar in concept to those used in other occupational radiation environments, would be worth investigating.

1.8.3 *Calibration*

***Recommendation 12*: Response data for the active and passive devices used should be determined for the following energy ranges as appropriate: protons from 10 to 800 MeV; high-Z, high-energy ions (*e.g.*, helium, carbon, silicon, iron) from 50 MeV n^{-1} to 1 GeV n^{-1}; electrons from 0.5 to 10 MeV; and neutrons from 1 to 180 MeV, in fields that are monoenergetic or quasi-monoenergetic, plus response data for fields which replicate the neutron field produced by the interactions of GCR with shielding material.**

The response characteristics of all the types of devices should be determined prior to use. This will normally be accomplished by a combination of experiment and calculation. The response determinations should normally be in terms of the quantity fluence. An exception would be for the determination of photon response, for which air or tissue kerma will be more appropriate. For the determination of the response characteristics of personal dosimeters, some irradiations should be performed on either an anthropomorphic phantom or a surrogate. Sufficient angle dependence of response data should

be available to estimate the isotropic response. Where needed and where available, recommended fluence to D and fluence to H conversion coefficients should be used.

1.9 Biodosimetry

***Recommendation 13*: NASA should continue to use biodosimetry as an ancillary component of radiation dose assessment for astronauts during extended space flights.**

The unique contribution of a biodosimetry program is that it provides an individual's dose assessment as estimated from a biological endpoint. Thus, it includes the response to the cumulative exposure and allows for an assessment of variations in individual sensitivity.

The fluorescence *in situ* hybridization (FISH) method is the most appropriate approach based upon available knowledge, technical availability, and experience. The current approach of using FISH for analyzing stable chromosomal translocations in peripheral lymphocytes both in preflight and postflight samples appears to be providing useful information on exposures. The establishment of calibration curves from individual preflight blood samples increases the sensitivity. Incorporating analysis of prematurely condensed chromosomes (PCC) will provide more analyzable cells within a sample. Improvements that can be envisaged are using chromosome painting probes and computer analysis that allow for assessment of translocations in all chromosomes at the same time. This method has been used successfully for tumor analysis. Automating the various FISH methods will increase throughput enormously.

Future considerations for biodosimetry in the area of genomics or molecular profiling, and technologies for measuring changes in cellular markers (in response to radiation) are noted in Section 7.

1.10 Immediate Dose Management and "As Low As Reasonably Achievable"

Immediate dose management refers to actions taken to address high transient exposures in the space radiation environment that could impact the conduct or completion of the mission or mission tasks.

***Recommendation 14*: Implementation of immediate dose management actions is the responsibility of all team members**

involved with work impacting the astronaut's exposure to radiation. A written plan (notably the flight rules mechanism) should contain the implementing procedures.

ALARA refers to actions taken to keep the doses in all cases as low as reasonably achievable, by balancing the mission objectives with practical dose reduction steps.

***Recommendation 15*: The RHO should assess the opportunities to apply ALARA. However, an effective ALARA program depends on everyone involved in the design and management of spacecraft and missions understanding the space radiation environment and its impact on astronaut radiation exposure. ALARA concepts should be incorporated into the design of the spacecraft and suits, the preflight planning (including the planned in-flight procedures), an in-flight review, and a postflight review.**

A number of suggestions bearing on immediate dose management and ALARA are given in Section 8.4. Three examples are:

- place radiation instruments at locations that provide the best real-time information on radiation exposure to the astronauts (for both immediate dose management and ALARA);
- provide areas where astronauts could be moved during high transient exposures, *i.e.*, move to a safe haven with additional shielding, and/or reposition the Space Shuttle (for immediate dose management); and
- provide areas used during off-duty hours and sleeping quarters with optimized shielding (for ALARA).

1.11 Radiation Safety Training

***Recommendation 16*: All personnel whose work impacts on astronaut radiation exposure should be trained in the techniques of radiation protection, with emphasis on implementation of immediate dose management and ALARA.**

The scope and depth of this training should be related to the corresponding level of impact the individual may have on astronaut dose. Section 8.5 presents suggested radiation protection training topics for astronauts, flight directors, flight surgeons, RHOs, other radiation safety professionals, and other individuals whose work can affect the astronaut's radiation exposure. All of these individuals should be trained in NASA's operational radiation safety program

and how immediate dose management and ALARA actions are proposed, implemented and made part of the review of actual events, especially those events involving high transient exposures.

***Recommendation 17*: Astronauts should be trained in the proper wearing and care of personal dosimeters. NASA should have a clear requirement and related training for the use of personal dosimeters by astronauts in-flight to ensure that each astronaut has an accurate mission and career dose record.**

1.12 Dosimetry Record

***Recommendation 18*: The dosimetry record constitutes the formal documentation for each astronaut's space-related radiation exposure history and should contain the cumulative dose from space flight, mission-related aviation activities, and mission-related biomedical research. The dosimetry record should contain, or be linked to, all the basic information that is necessary to obtain the required dose-limit quantities [gray equivalent (G_T) and effective dose (E)], and should include the low- and high-LET components of the radiation field.**

The dosimetry record, and the other supporting records linked to it, should be kept in a manner to satisfy a number of purposes as described in Section 9. These records are important to protect astronauts and to document radiation exposures. Other radiation exposure files, such as diagnostic and therapeutic medical radiation exposures from overall health care that are maintained in the medical department, should also be linked to the dosimetry record. However, the diagnostic and therapeutic medical radiation doses should not be added to occupational doses either for planning purposes or to limit occupational exposures.

***Recommendation 19*: Astronauts should receive an annual confidential report on their radiation dose assessment. The report should include career radiation doses in terms of effective dose (E) for stochastic effects and monthly and annual doses in terms of gray equivalent (G_T) for deterministic effects.**

***Recommendation 20*: The dosimetry record should be updated retrospectively whenever there is a systematic**

change in methodology or new information becomes available. Astronaut dose estimates should be adjusted whenever differences in the revised dose assessments exceed 30 percent of the original dose assessment (see discussion of accuracy in Sections 6.4.1 and 6.4.2).

Existing data related to space missions should be examined and compared to the dosimetry record to confirm that radiation dose estimates are based on all available data. If previously unanalyzed data are found, the data should be identified and representative samples of the data should be fully analyzed to determine the extent of their effect on current dose estimates.

2. Objectives of the Operational Radiation Safety Program for Astronauts

There are currently 160 astronauts in the U.S. Astronaut Office (137 United States astronauts and 23 other international astronauts) and approximately 40 Russian cosmonauts. The number of United States astronauts involved in the foreseeable future in LEO activities is anticipated to be between 200 and 250. Therefore, the operational radiation safety program for astronauts is for a small population. The overall objective to assess and control the radiation exposure of individual astronauts can be broken down as follows: (1) keep individual doses below the established dose limits to avoid deterministic effects; (2) keep accumulated doses over an astronaut's career below the established dose limits for stochastic effects; and (3) keep all astronaut doses as low as reasonably achievable, economic and social factors being taken into account (*i.e.*, follow the standard ALARA principle of radiation protection). In the context of near-Earth space activities, one must also take into account the mission requirements and the prevailing radiation conditions in LEO.

2.1 The Low-Earth Orbit Program

There are unique considerations in balancing mission objectives in LEO against the resulting levels of radiation exposure. The decision to incorporate Russian launch capabilities into the construction and operation of ISS placed the Station in a high-inclination orbit, comparable to the previous Russian Mir Space Station. The higher inclination places ISS in orbits that increase the residence time in radiation zones where the probability for high-exposure events from solar energetic particles and penetrating electrons in the outer radiation belts to occur is higher, compared to the original plan for a low-inclination orbit, which would have mostly avoided these radiation zones (NAS/NRC, 2000). This is a particularly important

consideration given the extensive extravehicular activities planned during ISS construction, which will also span the maximum of the current 11 y solar cycle.

A helpful description of the impact of the high-inclination orbit in which the astronauts will work is given in a report by the National Academy of Sciences/National Research Council (NAS/NRC, 2000). In the quoted text below, abbreviations have been spelled out in *italics*.

"As originally conceived in the early 1980s, ISS [*the International Space Station*] was to have a low-inclination (28.5 degrees), low-altitude (350 km) orbit. Then, the SAA [*South Atlantic Anomaly . . . part of the Van Allen Belts*] and GCRs [*galactic cosmic radiations*] would have been the only significant sources of radiation. SRAG [*the Space Radiation Analysis Group . . . the operational radiation safety unit at Lyndon B. Johnson Space Center*] knows how to design mission schedules to minimize astronaut exposure to the SAA during EVAs [*extravehicular activities . . . astronauts in space suits outside a Space Shuttle or station*], and there is little anyone can do to minimize GCR exposure. In 1993, however, the United States agreed with the Russian Federation to incorporate Russian launch capabilities into ISS construction and maintenance. That agreement brought with it the need to place ISS in a high-inclination orbit, essentially the same as that of the Mir space station, 51.6 degrees geographic [350 to 450 km altitude]. Consequently, ISS and the astronauts who construct and use it run the risk of being exposed to solar energetic particles and penetrating electrons in the horns of the outer belt. Exposure from these sources will be sporadic since SPEs [*solar particle events*] follow solar storms and HREs [*highly relativistic electrons*] follow magnetic storms and impacts by strong solar wind shocks. During the declining phase of a solar cycle—perhaps late in ISS construction—HRE events are also associated with times, lasting about a week, when solar wind streams are especially fast. Whereas satellite encounters with the SAA are as predictable as the tides, usually solar energetic particles, geomagnetic storms, and high-speed solar wind streams are not reliably predictable, nor is the intensity of the associated radiation event. The high-inclination orbit of ISS therefore introduces a new radiation risk factor.

"ISS construction plans call for approximately 33 U.S. shuttle flights and 10 Russian flights. The construction phase will extend from 1998 to 2004, which spans the maximum of solar cycle 23, when SPEs are expected to be most frequent. NASA estimates that during those years astronaut and cosmonaut construction crews may have to perform more than 160 EVAs totaling more than 1,100 hours. During those same years, there will be more than 400 additional

hours of EVAs by astronauts and cosmonauts to service and maintain the station. The total exceeds 1,500 hours, or 1,000 ISS orbits, of EVA time."

The very real potential that high transient radiation doses to astronauts will occur occasionally during construction and operation of ISS was also documented by NAS/NRC (2000). The following two statements from the report address the potential for high radiation doses from SPEs and relativistic electrons from the outer belt, respectively.

". . . the high-latitude zones to which solar energetic particles have access show a marked tendency to widen over the polar latitudes reached by the ISS orbit when SPEs are in progress, a tendency that becomes more pronounced as SPEs intensify. Two storms during 1989, near the maximum of the last solar cycle, illustrate the point. The areas around the poles accessible to SPE particles enlarged until they engulfed more than a quarter of the ISS orbit, and the flux of particles was high enough to have pushed an astronaut over the short-term limit for irradiation of skin and eyes during a single ill-timed 6-hour EVA."

"For a portion of nearly every day, some fraction of the ISS orbit lies within the outer radiation belt, where relativistic electrons reside. At its maximum, this fraction is about 20 percent. During occasions called relativistic electron events, which happen on average about once per month and last several days, the intensity of relativistic electrons in the belt increases by up to four orders of magnitude. When the intensity of relativistic electrons is greatest, a single ill-timed EVA could deliver a radiation dose big enough to push an astronaut over the short-term limit for skin and eyes."

NAS/NRC (2000) also made recommendations for improving the real-time forecasting of space weather events such as solar wind conditions (particularly during the current 11 y solar maximum cycle) and outer radiation belt conditions, and the need for improved coordination of existing and future space weather forecasting capabilities within NASA, and with the National Oceanic and Atmospheric Administration and the U.S. Air Force. Most of these improvements will take some time to implement.

2.2 Dose Limits for Astronauts

NCRP reviewed the evolution of dose limits for astronauts and recommended dose limits specifically for astronauts in LEO in NCRP Report No. 98 (NCRP, 1989). NCRP recently updated the dose limits

in NCRP Report No. 132 (NCRP, 2000a) to take account of more recent information on estimates of radiation health effects. The dose limits for bone marrow, lens of the eye, and skin are for protection against deterministic effects. The career dose limits are for protection against delayed stochastic effects and are based on a lifetime excess risk of cancer mortality of three percent.[1] The main features of the current dose limits and the quantities used to assess astronaut exposures against the dose limits are summarized in Table 2.1.

2.2.1 *Deterministic Limits*

The dose limits for deterministic effects are expressed in terms of gray equivalent, where gray equivalent is the mean absorbed dose in an organ or tissue modified by a recommended value, for radiation protection purposes, of the relative biological effectiveness (*i.e.*, a best estimate) of a given particle type, as given in NCRP (2000a).[2] In this Report, a conventional notation is used for the quantity gray equivalent, namely:

$$G_T = R_i D_T, \tag{2.1}$$

where G_T is gray equivalent, R_i is the recommended value of the relative biological effectiveness for particle type i referred to above, and D_T is the mean absorbed dose in an organ or tissue.

The values for R_i are given in Table 2.2. The dose limits for deterministic effects are given in Table 2.3. The special name for the unit of D_T is gray (Gy) and the name of the unit for G_T is gray equivalent, with the notation Gy-Eq (NCRP, 2000a).

2.2.2 *Stochastic Limits*

The career limits for delayed stochastic effects are expressed in effective dose (E), where:

$$E = \sum_T w_T H_T. \tag{2.2}$$

[1]The recommended dose limit for an astronaut entails a similar lifetime excess risk of cancer mortality (three percent) as the dose limit for a terrestrial worker, if both an astronaut and a terrestrial worker reached the maximum value of the respective dose limit during their working lifetimes.

[2]NCRP (2000a) recommended that the mean absorbed dose in an organ or tissue (D_T) be modified by the recommended values for relative biological effectiveness to adjust for radiation quality for deterministic effects because the usual formulation for equivalent dose (H_T) is obtained by applying radiation weighting factors (w_R) which are applicable to stochastic effects.

TABLE 2.1—*Radiation protection quantities for space radiation (NCRP, 2000a).*

Quantity	Deterministic Effects	Stochastic Effects
Mean absorbed dose in an organ or tissue	Mean absorbed dose (D_T) (in Gy) For irradiated portion of tissue	Mean absorbed dose (D_T) (in Gy) For entire organ or tissue
D_T weighted for the relative biological effectiveness of the radiation or particle type	Gray equivalent (G_T) (in Gy-Eq) Weights D_T by a recommended value for relative biological effectiveness for the particle type i (R_i); R_i values derived from ICRP (1989). Tissues are lens of eye, skin and bone marrow (Table 2.2)	Equivalent dose (H_T) (in Sv) For space radiation, adopts the relationship $\overline{H}_T \approx H_T$ (NCRP, 2000a), where $\overline{H}_T$ is the organ dose equivalent (ICRU, 1993) (Section 2.2.2). Uses the $Q(L)$ relationship in ICRP (1991), ICRU (1993), and NCRP (1993) to evaluate $\overline{H}_T$ (Section 2.2)
Tissue weighting factor	Not applicable	Uses the tissue weighting factors for radiation detriment (w_T) from ICRP (1991) and NCRP (1993)
Dose-limit quantities	Gray equivalent (G_T) (in Gy-Eq)	Effective dose (E) (in Sv) $E = \sum_T w_T H_T$, from ICRP (1991) and NCRP (1993). $\overline{H}_T$ is the approximation for H_T, determined as given above
Dose limits	G_T limits (in Gy-Eq) For 30 d and annual, all three tissues. For career, lens of eye and skin (Table 2.3)	E limits (in Sv) For 10 y career, gender and age-specific, males and females, for ages at exposure of 25, 35, 45 and 55 y. Based on three percent excess lifetime risk of cancer mortality (Table 2.4)

TABLE 2.2—*R_i values for converting D_T to G_T for deterministic effects (adapted from ICRP, 1989; NCRP, 2000a).*[a]

Particle Type	R_i (range for value)
1 to 5 MeV neutrons	6.0[b] (4–8)
5 to 50 MeV neutrons	3.5[b] (2–5)
Heavy ions (*e.g.*, helium, carbon, neon, argon)	2.5[c] (1–4)
Protons >2 MeV	1.5 (—)

[a]RBE values[3] for late deterministic effects are higher than for early effects in some tissues and are influenced by the doses used to determine the RBE values.

[b]There are not sufficient data on which to base an R_i for early or late effects[4] induced by neutrons of energies <1 MeV or greater than about 25 MeV. However, based on the induction of chromosome aberrations, using 250 kVp x rays as the reference radiation, RBE values for neutrons <1 MeV are comparable to those for fission spectrum neutrons. It is reasonable to assume that RBE values for neutrons >50 MeV will be equal or less than those for neutrons in the 5 to 50 MeV range.

[c]There are few data for the tissue effects of ions with $Z > 18$, but RBE values for iron ions ($Z = 26$) are comparable to those for argon. Based on the available data, an R_i of 2.5 for heavy ions is reasonable. One possible exception is cataract of the lens of the eye because high RBE values for cataracts in mice have been reported.

H_T is the equivalent dose and w_T is the tissue weighting factor (ICRP, 1991; NCRP, 1993). The career limits are specified by gender and age, and take into account the gender and age-adjusted cancer mortality risk coefficients (*i.e.*, the differential risk per unit dose) for the same overall three percent excess lifetime risk. The career dose limits are given in Table 2.4.

The quantity E is obtained as follows for the space radiations. First, the dose equivalent (H) is defined at a point in tissue and can be directly measured (ICRU, 1993). H is given by:

$$H = \int_L Q(L)\, D(L)\, \mathrm{d}L. \tag{2.3}$$

$Q(L)$ is the quality factor (Q) for particles as a function of LET (L) and $D(L)$ is the spectral distribution in terms of L of the absorbed

[3]The acronym RBE refers to experimental data on relative biological effectiveness.

[4]The symbol R_i refers to recommended values of relative biological effectiveness (*i.e.*, best estimates) for radiation protection purposes that are used for obtaining G_T, as discussed in NCRP (2000a).

TABLE 2.3—*Recommended G_T limits for deterministic effects (all ages) (NCRP, 2000a).*

	G_T Limit (Gy-Eq)		
	Bone Marrow	Lens of the Eye	Skin
Career	—[a]	4.0	6.0
1 y	0.50	2.0	3.0
30 d	0.25	1.0	1.5

[a]The career limits for stochastic effects given in Table 2.4 are considered to be more than adequate for protection of bone marrow against deterministic effects for a career. The career limits are expressed in terms of E. The w_R values (for stochastic effects) used to convert D_T to E are based on $\overline{Q}(L)$ and are higher than the R_i values (for deterministic effects) used to convert D_T to G_T. Therefore, there is no need for a career deterministic limit for the bone marrow. The career stochastic limit is more restrictive and would always be expected to result in a lower D_T to the bone marrow for irradiation conditions in space.

TABLE 2.4—*Ten-year career E limits based on three percent excess lifetime risk of fatal cancer (NCRP, 2000a).*[a,b]

Age at Exposure[b] (y)	E Limit (Sv)	
	Female	Male
25	0.4	0.7
35	0.6	1.0
45	0.9	1.5
55	1.7	3.0

[a]A three percent excess lifetime risk of cancer mortality has additional components of detriment associated with it, namely the risk of heritable effects (0.6 percent) and the detriment associated with nonfatal cancer (also 0.6 percent), for a total detriment of 4.2 percent. These nominal risks are as given in ICRP (1991) and NCRP (1993).

[b]The career E limits are for a 10 y career beginning at the age of first exposure. For situations in which careers differ in length from 10 y, or for careers that start at other than the designated ages, additional advice is provided in Section 6.4 of NCRP (2000a).

dose at the point (D). For the complex mixtures of high- and low-LET radiations experienced in LEO, the practice in the space radiation protection community is to average the point quantity H over the organ or tissue of interest by means of computational models to obtain the organ dose equivalent (ICRU, 1993), which is required for radiation protection purposes but cannot be directly measured. In this Report, the symbol $\overline{H}_T$ is used for the quantity organ dose equivalent. NCRP (2000a) adopted $\overline{H}_T$ as an acceptable approximation for H_T for stochastic effects: Therefore, in general terms:

$$\overline{H}_T = M_T{}^{-1} \int_x \int_L Q(L)\, D(L)\, \rho(x)\, \mathrm{d}L\, \mathrm{d}x, \tag{2.4}$$

where there is a second integration over the points x in tissue T with tissue density $\rho(x)$ and total mass M_T. For the radiations in LEO, the quantities $\overline{H}_T$ and H_T are interchangeable for radiation protection purposes. The methods used to evaluate $\overline{H}_T$ are discussed in Sections 5 and 6. Therefore, $E \approx w_T\, \overline{H}_T$, and E, H, H_T and $\overline{H}_T$ are expressed in sievert (Sv).[5]

The $Q(L)$ relationship is given in ICRP (1991), ICRU (1993), and NCRP (1993), where:

$$\begin{aligned} Q(L) &= 1 && \text{for: } L < 10 \text{ keV } \mu\text{m}^{-1} \\ Q(L) &= 0.32\, L - 2.2 && \text{for: } L = 10 \text{ to } 100 \text{ keV } \mu\text{m}^{-1} \\ Q(L) &= 300\, L^{-1/2} && \text{for: } L > 100 \text{ keV } \mu\text{m}^{-1} \end{aligned} \tag{2.5}$$

The $Q(L)$ relationship is consistent with current knowledge of the general trend of relative biological effectiveness for cell killing and induction of mutation from HZE particles.

2.3 Operational Radiation Protection Considerations

This Report concentrates on the specific technical considerations necessary to implement an operational radiation safety program for the principles of dose limitation and ALARA for astronauts working in LEO. In particular, the Report describes the radiation components

[5]This procedure for obtaining E for space radiations differs from that used for terrestrial radiation environments, in that $\overline{H}_T$ (calculated as given above) replaces $H_T = w_R\, D_T$, where w_R (for external radiation) is a nominal value based on the type and energy of the radiation incident on the body (ICRP, 1991; NCRP, 1993). The practice of obtaining $\overline{H}_T$ permits more complete consideration of the $Q(L)$ relationship for the complex space radiation environments.

of the space environment (Section 4) from the perspective of the measurements needed to support the dose assessment approach (Section 5) used to generate values for the radiation protection quantities recommended for space activities, that is, G_T, $\overline{H}_T$ (*i.e.*, the surrogate for H_T), and E. A key aspect of the Report is the recommendations for collection of observable data (Section 6) in both active and passive modes. The observable data help implement the recommended dose assessment approach, in conjunction with an array of radiation transport models and codes (Section 5). These recommendations are developed fully in this Report, taking into account the practical limitations on the radiation detection devices and protective systems that can be available in-flight.

The availability of credible estimates for the recommended radiation protection quantities would help accomplish the following objectives of the operational radiation safety program:

- to facilitate actions, both in advance of a mission and in-flight, that respond to space radiation conditions or mission decisions that in turn significantly influence the levels of radiation exposure to the astronauts, and radiation protection decisions that in turn significantly influence the conduct of the mission;
- to collect and record astronaut doses for individual mission and cumulative career records. These records can also be used in prospective radiation-related health studies of the Astronaut Corps or to assist retrospective dosimetry to update the records for previous activities of individual astronauts; and
- to identify, plan and inform practical ALARA actions to avoid unnecessary levels of radiation exposure. These ALARA actions would address both radiation exposures that are adjunct to a mission (*e.g.*, ground-based space-related biomedical research) and those that occur in-flight (*e.g.*, mission experiments using radiation sources, or avoidance of higher exposure locations in space vehicles when an ongoing mission task or activity does not require presence there).

3. Current Management of Astronaut Radiation Safety Program

The management of radiation dose received by astronauts in LEO involves many individuals. Typically, astronauts do not play an active role in decision making and policy regarding radiation issues. Instead, the flight director and flight surgeon direct their actions, with the help of radiation experts.

At the Lyndon B. Johnson Space Center (JSC), there are two radiation expert resources, SRAG and the RHO. These individuals work with the medical officers, the payload officers, mission planners, outside agencies, and the flight directors to provide radiation expertise in developing and interpreting radiation flight rules that govern the conduct of a flight, from mission planning through the end of a space flight, with regard to crew radiation exposure and adherence to ALARA. Dose limits and administrative levels are developed and are then written as flight rules by NASA radiation experts.[6] The flight rule approval process involves a variety of NASA managers from different departments so that management becomes very familiar with the rules and supporting rationale. In the process of approving flight rules, program management is educated and trained on the risks associated with radiation exposure. A flight director chairs the Flight Rule Change Board, which approves and incorporates all new rules and rule changes. Once approved and incorporated, the flight rules are "tested" during simulations to ensure proper interpretation and response to a given scenario.

3.1 Flight Rules for Management of Dose

The flight rules are a comprehensive set of rules, reviewed and updated continuously, governing all the procedures and operation

[6]Dose limits are developed through input from NCRP and the Occupational Safety and Health Administration recommendations. Administrative levels are developed internally by NASA.

of space vehicles. Extensive rules regulate management of normal operations and off-nominal operations of all Space Shuttle and ISS systems, such as main engines, life support, computer, electrical, and hydraulic systems. The flight rules that govern measurement of the radiation environment and management of crew exposure to radiation are contained in one section of the flight rules titled "Space Environment," which incorporates the following:

- general definitions which define event conditions (*e.g.*, SPE, energetic SPE, geomagnetic storm) and ALARA;
- radiation subsystem loss definitions which define what determines monitoring and measuring equipment to be out of service;
- crew exposure management which defines actions to assist in management of the crew exposures;
- rules that are in place to maintain exposure ALARA and below legal limits;
- radiation subsystem management which are special rules for radiation equipment operation; and
- designated maintenance items which are additional criteria that indicate hardware may be inoperable.

Administrative limits or "action levels" are published in the flight rules to serve as a guide, with ALARA, to initiate more stringent dose management activities for a mission if there is a higher than projected accumulated exposure. The administrative limits for a mission are monthly, cumulative limits 5 mGy above the projected absorbed dose for that part of the solar cycle. There are also 30 d and 1 y maximum allowable exposure limits to manage acute exposures. If the exposure on a particular mission is greater than expected, actions are detailed in the flight rules to remain within the crew administrative limits. Some actions that the ground and crew might consider are: restricting crew location within ISS, rescheduling EVAs, reducing the number of EVAs, terminating an EVA in progress, deferring ISS reboost, shortening crew time in orbit, or returning the crew to Earth. Crew safety is the highest priority. Many factors determine the course of action during a flight. SRAG, the RHO, and the flight surgeon work with the flight director to determine the best course of action when these rules are considered.

The NASA term "administrative limit" or "action level" corresponds to the term "administrative level" used elsewhere in this Report. The NASA term "exposure limit" corresponds to the term "dose limit" used elsewhere in this Report.

There is a set of flight rules governing the conduct of a Space Shuttle mission (*e.g.*, NASA, 2000a), and a set governing the conduct of an ISS mission (*e.g.*, NASA, 2000b).

3.2 Biomedical Research

Because astronauts may also receive occupational radiation dose during the conduct of biomedical experiments associated with space flights, these experiments need to be approved for funding and performance during flight at NASA Headquarters. Exposure to radionuclides and x rays associated with biomedical experiments may contribute substantially to an astronaut's total dose. Any biomedical experiment involving radiation exposure is approved by an expert NASA radiation panel. The RHO, a flight surgeon, and a senior medical officer are among those who serve on this panel. After approval by this group, the JSC Institutional Review Board reviews the experiment and may give approval. As with all biomedical experiments, astronauts may choose whether or not to volunteer to participate. If astronauts choose to volunteer, they do so with informed consent.

3.3 Individuals Involved in Management of Dose

3.3.1 *Astronaut*

Approximately 160 astronauts are active in the U.S. Astronaut Office. One or two astronauts (generally astronauts with medical backgrounds) represent the Astronaut Office's position regarding radiation protection policy, procedures and concerns in the various meetings and committees. Prior to their flight, if radiation exposure is expected to be more than minimal, the affected astronauts may participate more actively in the decision-making process concerning their particular flight. In general, astronauts assigned to fly longer missions on ISS show more interest in radiation protection issues and take a more active role in developing procedures to reduce exposure, such as determining the "best" sleep location.

3.3.2 *Flight Director*

Approximately 20 flight directors are stationed at JSC. Each mission is assigned a "lead" flight director who provides input and makes decisions during the planning and training period preflight. During a mission, the flight director is the final decision maker in the Mission Control Center with regard to all aspects of the mission including mission replanning, and flight rule interpretation and implementation.

The flight director weighs all risks and benefits during this process with the aid of systems experts on the flight control team and relies heavily on the RHO, SRAG and the flight surgeon when decisions regarding radiation protection issues need to be made. The flight director weighs the radiation risks against the risks and mission impacts of altering other flight procedures (for example, delayed or shortened EVA, or early deorbit and landing at a contingency landing site). The Chief of the Flight Director's Office chairs the NASA Flight Techniques Board that approves flight rules.

3.3.3 *Flight Surgeon*

Approximately 15 NASA flight surgeons are stationed at JSC. When serving as a crew surgeon for a specific flight crew, the flight surgeon is responsible for that crew's health and safety during all aspects of flight training, mission execution, and postflight rehabilitation and recovery. The flight surgeon briefs the crew preflight and postflight regarding radiation protection issues and personal radiation dose. During a space flight the flight surgeon is the primary interface between SRAG and the flight director in the Mission Control Center when issues arise pertaining to radiation exposure. During a mission, the flight surgeon and SRAG provide expert flight rule interpretation for the flight director and mission management, and assist in mission replanning, when necessary. Generally, one member of the Flight Surgeon's Office is designated to be the "resident expert" on radiation protection issues. This flight surgeon serves on various committees and groups that address radiation protection issues. One committee is the Radiation Integrated Product Team, which is co-chaired by the RHO and the flight surgeon and also includes experts outside of NASA. This committee meets quarterly to discuss and formulate possible flight research projects, and to consider operational issues, such as adequacy of onboard radiation monitoring. This flight surgeon is also the point of contact to communicate new information to the rest of the flight surgeon community.

3.3.4 *Radiation Health Officer*

The RHO provides recommendations to minimize crew exposures through design and development of radiation protection strategies, in NASA policy documents, during mission planning, and real-time during space missions. The RHO tracks crew exposures against career limits, provides risk interpretation for acute exposures, and interfaces with the RHOs from the international partners.

3.3.5 *Space Radiation Analysis Group*

SRAG, along with the RHO, are the NASA radiation specialists responsible for promoting ALARA and ensuring compliance with procedures to implement ALARA during all phases of mission design, planning and flight. They serve as the interface to all other groups and individuals in the space flight program who have responsibilities that can affect crew radiation exposure. With the exception of the flight surgeons, no other individuals involved in mission planning and operational decision making have in-depth training or experience in radiation protection issues. During space flights, SRAG has the following responsibilities: monitoring of space weather; space radiation environment contingency response and analysis; radiation instrument operations; tracking of crew daily and cumulative dose; EVA planning, support and monitoring; and interfacing with outside support groups (*i.e.*, National Oceanic and Atmospheric Administration, U.S. Department of Defense). During a mission, SRAG interfaces with mission planners and flight controllers, including the flight director, to update mission significant radiation events and provide expertise, particularly when transient events in the space radiation environment produce a potential for high doses to the astronauts.

4. Radiation Environment in Low-Earth Orbit

The radiation environment external to a spacecraft in LEO consists of electrons, positrons, neutrons, protons and heavier nuclei (up to Z = 92). Sources include: GCR from deep space; SPEs produced by coronal mass ejections or by acceleration in solar flare events; particles trapped in Earth's magnetic field; and scattering from Earth's atmosphere (albedo neutrons, electrons and protons). Energies range from a few electron volts for trapped electrons and albedo neutrons to in excess of 10^{14} MeV for GCR ions.

The space radiation environment is modulated by spatial and temporal factors including the 11 y solar cycle and the solar wind, and Earth's magnetic field, which traps some particles and deflects others. The particle distributions are sensitive to both inclination and altitude. GCR is approximately isotropic in deep space, but in LEO the GCR intensity is modulated by the geomagnetic field. Due to the shape of Earth's magnetic field lines, high-inclination Space Shuttle flights and ISS (51.6 degrees) are exposed to higher GCR fluxes than are low-inclination Space Shuttle flights (*e.g.*, 28.5 degrees). Earth's magnetic field varies in strength and configuration over timescales from days to years. It is influenced by changes in activity on the surface of the sun over the 11 y solar cycle, but can also exhibit acute changes as a result of solar storms. The January 1997 geomagnetic storm moved the South Atlantic Anomaly (SAA) by nearly 80 km (Badhwar, 2001).[7]

Protons and electrons are trapped in belts at various altitudes and inclinations. If a spacecraft orbit intersects a belt, the intensity of the charged particles and the corresponding dose rate onboard will increase. These belts are slowly modulated by solar activity; however, the major influence on dose rate is the frequency and duration of spacecraft transits through the belts, which are on the order of minutes to tens of minutes in LEO. Active dosimeters can distinguish between trapped particles and GCR by separating the data into time

[7] Badhwar, G.D. (2001). Personal communication (Lyndon B. Johnson Space Center, National Aeronautics and Space Administration, Houston, Texas).

periods corresponding to the parts of the orbit that intersect the trapped radiation belts.

Coronal mass ejections or flares can generate high intensities of charged solar energetic particles, primarily protons, that may eventually intercept the spacecraft. The occurrence of SPEs is unpredictable. Real-time detectors are needed to confirm the onset and duration of an event in order to initiate countermeasures in the spacecraft and to avoid high exposures during an EVA.

Although an SPE may last for a short period of time, disturbances of the trapped belts, and consequently elevated radiation levels, in particular the intensity of electrons outside of the spacecraft, can persist for times on the order of several days. Most of these electrons will not penetrate the wall of the spacecraft, but could penetrate the space suits worn during EVA, resulting in substantial doses to the skin and eyes. Time-dependent factors are discussed in greater detail in Appendix A.

Nuclear interactions of neutrons, protons and heavier nuclei with spacecraft, space suits, Earth's atmosphere, and the human body produce secondary particles that add to the radiation field.

A more detailed summary of the near-Earth radiation environment and the factors that modulate it can be found in NAS/NRC (2000) and NCRP (2000a) and references therein.

Radiation monitoring instrumentation and measurement strategies vary according to charge, particle type, energy, and where the measurements are made. For purposes of this Report, we will classify the radiation environment according to particle types and energies and where the measurements are to be made, namely: outside the spacecraft, inside the spacecraft, and inside EVA suits. The figures in parentheses are the approximate particle ranges of interest in energy (in MeV) and the unrestricted linear energy transfer (L_∞) in water (in keV μm^{-1}).

4.1 Trapped Electrons (0.5 to 6 MeV; ~0.2 keV μm^{-1})

Trapped electrons with energies >0.5 MeV will penetrate some parts of EVA suits. Electrons experience primarily electromagnetic interactions. Because they are singly charged point particles and not subject to strong nuclear interactions, secondary particle production is limited to electrons, positrons and photons (through annihilation and bremsstrahlung), which do not contribute substantially to the radiation dose. Principal measurement locations are outside the spacecraft and inside EVA suits. For aluminum shielding, primary

electrons are the dominant source of dose only for shields with areal densities <0.15 g cm^{-2} (NCRP, 2000a). The relative importance of electron and proton doses inside EVA suits is under study (Wilson *et al.*, 2001; Zeitlin, 2000[8]).

4.2 Reentrant and Splash Albedo Electrons (1 MeV to >1 GeV; 0.2 to >3 keV μm^{-1})

Reentrant electrons are the decay products of unstable nuclei produced by the nuclear interactions of trapped GCR ions. Splash albedo electrons are scattered upward by interactions in the atmosphere. The high energies of the parent nuclei boost these electrons to much higher energies than trapped electrons. Badhwar *et al.* (2001) recently made a detailed study of the contribution of reentrant and albedo electrons at ISS altitude and inclination to the dose to the bone marrow during EVA. They found the dose to be more than 10 times greater than the dose from trapped electrons. Moreover, the hardness of the reentrant electron spectrum makes the dose from those electrons rather insensitive to the addition of shielding, at least at the level practical for an EVA suit. So while the trapped electron dose will still dominate in thinly shielded locations, the reentrant and splash electron dose dominates as the shielding thickness is increased. The high energies of these electrons dictate that measurements be made inside and outside the spacecraft, and inside EVA suits.

4.3 Trapped Protons (<10 MeV; >5 keV μm^{-1})

Protons at energies <10 MeV (on the order of the nuclear binding energy) will produce slow target fragments through compound nucleus formation and decay. However, they will not penetrate spacecraft or EVA suits and therefore are not a measurement objective.

4.4 Trapped and Solar Protons and Light Nuclear Particles (10 to 400 MeV; 0.3 to 5 keV μm^{-1})

Protons with energies greater than approximately 10 MeV will penetrate EVA suits and spacecraft walls, and more energetic protons

[8] Zeitlin, C.J. (2000). Personal communication (Lawrence Berkeley National Laboratory, Berkeley, California).

will penetrate into locations that are more heavily shielded, *e.g.*, by equipment racks or storage lockers. Nuclear interactions in materials and tissue will produce low-energy, highly ionizing target fragments and will knock out light nuclear particles (Z = 1, 2 and neutrons) with velocities comparable to that of the projectile. There is a small component of low-energy SPE light ions, but they are thought to contribute a negligible amount to radiation risk (NCRP, 2000a). Radiation monitors and dosimeters sensitive to high-energy SPE protons and light nuclear particles can be placed inside and outside EVA suits and spacecraft.

4.5 Galactic Cosmic Radiation Ions and High-Energy Secondary Fragments (>50 MeV n^{-1}; Z > 1; 1 to 1,000 keV μm^{-1})

The GCR ion spectrum peaks at energies around a few hundred MeV n^{-1}. Charged particles at these energies can penetrate into the interior at many spacecraft locations and through substantial thicknesses of tissue. Nuclear interactions will produce high- and low-energy secondary charged particles, which are often more penetrating, including pions. The high-energy secondary particles arise mainly from projectile fragmentation and will have velocities comparable to that of the primary. Pions are created in nuclear interactions above a few tens of million electron volts. The contribution of pions to the dose is not known, but is under study at this writing (Wilson, 2000).[9] Primary and secondary ions over a wide energy range will be present at all locations of interest, both inside and outside EVA suits and spacecraft.

4.6 Charged Target Fragments (<10 MeV n^{-1}; 2 to 1,200 keV μm^{-1})

Target fragments (*i.e.*, pieces of the struck atomic nucleus) produced in nuclear interactions have very short range and therefore deposit a large amount of energy very close to the location where they are created. If this is within the human body, they can produce substantial biological effects. The most probable energy is <5 MeV,

[9] Wilson, J.W. (2000). Personal communication (Langley Research Center, National Aeronautics and Space Administration, Hampton, Virginia).

the average kinetic energy is 10 MeV, and the distribution falls to one percent of the peak at 40 MeV (Shavers, 1999; Wilson *et al.*, 1988a; 1988b). Measurements of these particles would be needed only inside space suits and spacecraft.

4.7 Neutrons (0.1 to 500 MeV)

Neutrons present in LEO are produced by nuclear interactions in the upper atmosphere (albedo neutrons), and by interactions of high-energy protons and heavier nuclei in shielding and tissue. The neutrons in turn interact with atomic nuclei to produce highly ionizing charged secondary particles.

Measurements at high orbital inclination (57 degrees, slightly higher than the 51.6 degrees for ISS) showed that at moderately shielded locations most of the neutron H came from neutrons above 1 MeV (Badhwar *et al.*, 1996a). Armstrong and Colborn (1992) calculated that for GCR-produced neutrons, almost half of the neutron H is from neutrons above 10 MeV, and Armstrong recently calculated that up to 20 percent of the total H on ISS from all particle types will be from neutrons with energies $>$10 MeV (NASA, 2001).

A recent workshop considered the contribution of neutrons to radiation dose to crews in LEO (NASA, 2001). The workshop concluded that no single detector can cover the wide energy range of interest, and that the detectors currently in use have not been adequately calibrated. TLDs used on the Space Shuttle and ISS are "almost completely insensitive to neutrons" and "measure absorbed dose and not the biologically important dose equivalent." Because of the high penetrating power of neutrons, measurements are needed internal and external to spacecraft, and inside EVA suits.

4.8 Summary for Particle Types

Table 4.1 summarizes the locations where radiation measurements are needed as a function of the particle types discussed in Section 4.1 through 4.7. The relative contributions to D and H from each component (including the secondary radiation) at each location will vary according to several factors, including the spacecraft internal mass distribution, the EVA suit design and materials, and the site of interest within the human body. As a rule, D due to electrons will be insignificant for all but the most thinly shielded locations of an EVA suit.

TABLE 4.1—*Summary of locations where radiation measurements are needed, as a function of particle types, for operations in LEO.*

	EVA Suit (internal)	Spacecraft (external)	Spacecraft (internal)
Trapped electrons	X	X	—
Reentrant and albedo electrons	X	X	X
Trapped protons (<10 MeV)	—	—	—
Protons and light nuclear particles (>10 MeV)	X	X	X
GCR ions and secondary charged fragments	X	X	X
Charged target fragments	X	—	X
Neutrons	X	X	X

5. Approach to Dose Assessment for Astronauts

Dose assessment requires evaluation of specific quantities to manage exposures at the time of operation and for implementation of career and short-term limits. The basic quantities to be evaluated are given in Table 2.1 and the corresponding limitations are given in Tables 2.3 and 2.4. The means by which dose is evaluated in practice will be discussed in this Section, as well as the relationship of radiation environment models, shielding models, and radiation monitoring both inside the spacecraft and outside.

A basic quantity is mean absorbed dose in an organ or tissue (D_T). It is calculated from the distribution of D at points in the relevant organ or tissue in terms of the L contributions at the specific points [$D_i(L,x)$], and averaged over the organ or tissue, as shown below. The dose contribution from particles of type i with L at point x is:

$$D_i(L,x) = \int dt \int \rho(x)^{-1} L \, \Phi_i[E_i(L),\boldsymbol{\Omega},x,t] \mid dE_i(L)/dL \mid d\boldsymbol{\Omega}, \qquad (5.1)$$

where $\Phi_i[E_i(L),\boldsymbol{\Omega},x,t]$ is the fluence of particle type i at the point x at time t with energy $E_i(L)$ (the multi-valued energy for given L of a particle i) moving in direction $\boldsymbol{\Omega}$, L is the linear energy transfer in appropriate units, $|dE_i(L)/dL|$ is the multi-branched derivative, and $\rho(x)$ is the tissue mass density.

D_T is evaluated as the mean absorbed dose over all radiation components i and organ tissue T as:

$$D_T = M_T{}^{-1} \int_x \rho(x)\, dx \sum_i \int D_i(L,x)\, dL, \qquad (5.2)$$

where M_T is the total tissue mass.

The dose equivalent is defined at a point x in the tissue as:

$$H(x) = \sum_i \int Q_i[L_i(E)]\, D_i(L,x)\, dL, \qquad (5.3)$$

where $Q_i[L_i(E)]$ is the quality factor for particle type i with $L_i(E)$ (the multi-valued L for a given E of a particle i).

The organ dose equivalent ($\overline{H}_T$) is determined as an average of H over all points in the organ or tissue as:

$$\overline{H}_T = M_T^{-1} \int_x \rho(x)\, H(x)\, dx \tag{5.4}$$

where the bar denotes the averaging process and T denotes the organ or tissue over which the average is performed. Since, for space radiations, $\overline{H}_T$ is an acceptable approximation for H_T (Section 2.2), the effective dose (E) is then given as:

$$E = \sum_T w_T H_T \approx \sum_T w_T \overline{H}_T. \tag{5.5}$$

The evaluation of gray equivalent (G_T) in a specific tissue of type T is given in terms of the field-weighted quantities as:

$$G_T = \sum_i R_i D_{T,i} \tag{5.6}$$

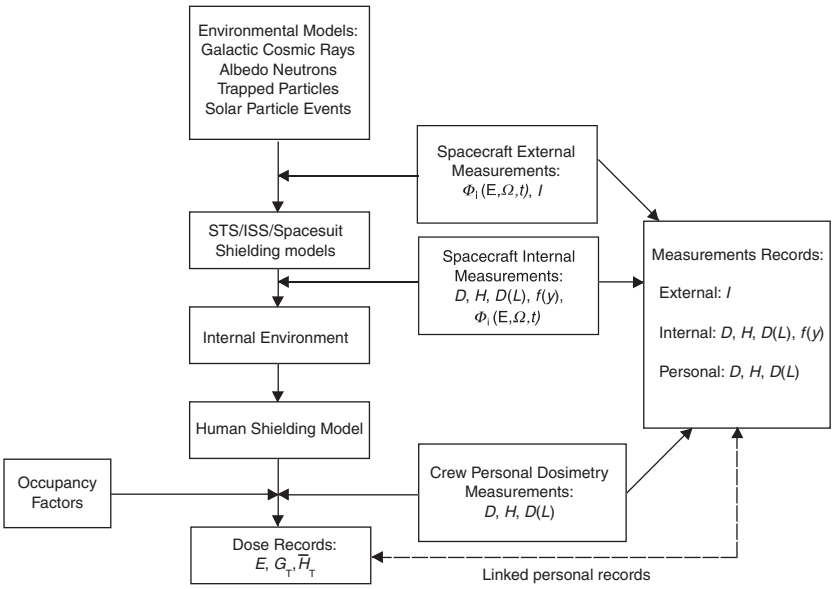
where $D_{T,i}$ is the mean absorbed dose to tissue T from the interior field component i and R_i is the recommended value of the relative biological effectiveness (*i.e.*, a best estimate) for the specified particle type i given in Table 2.2. Note that G_T is not a point function and leads to computational complexity. Note that the R_i values are energy independent except those for neutrons (Table 2.2). A dose-averaged value for neutrons ($\overline{R}_{n,T}$) can be evaluated for specific tissues knowing the neutron field and the appropriate tissue dose conversion factors [$C_{n,T}(E)$] (ICRP, 1996; ICRU, 1998; Yoshizawa *et al.*, 2000) as:

$$\overline{R}_{n,T} = \frac{\int dt \int R_n(E)\, C_{n,T}(E)\, \Phi_n(E,\boldsymbol{\Omega},x,t)\, dE\, d\boldsymbol{\Omega}}{\int dt \int C_{n,T}(E)\, \Phi_n(E,\boldsymbol{\Omega},x,t)\, dE\, d\boldsymbol{\Omega}}, \tag{5.7}$$

where $\Phi_n(E,\boldsymbol{\Omega},x,t)$ is the ambient neutron interior fluence at the astronaut location in the spacecraft. The use of $\overline{R}_{n,T}$ reduces the computational complexity but there is as yet insufficient RBE data for most radiation types to evaluate these quantities for the full interior radiation field. NCRP (2000a) has discussed the use of conservative values for R_i components for which RBE values are unknown (Table 2.2).

Figure 5.1 outlines the dose assessment scheme for use in LEO. The knowledge required for evaluation of organ or tissue dose and the dose-limit quantities for the astronaut includes the:

- radiation environment at the exterior surface of the spacecraft
- relationship of the exterior radiation environment to the interior radiation environments of the Space Shuttle, ISS, and space suit



List of quantities:

Φ_i(E,Ω,t): external or internal fluence; with particle type i, time t, energy E, direction Ω
I: ionization current in a tissue-equivalent ion chamber
D: absorbed dose, at a point
H: dose equivalent, at a point
$D(L)$: absorbed dose distribution over L, at a point
$f(y)$: frequency distribution of lineal energy
E: effective dose
G_T: gray equivalent
$\overline{H}_T$: organ dose equivalent; approximation to equivalent dose (H_T)

Fig. 5.1. Recommended dose assessment method.

- timeline of astronaut activity within those environments
- transmission of radiation from the internal radiation environment to specific organ tissues
- relationship of the organ exposure field to organ or tissue dose
- relationship of organ or tissue dose to the dose-limit quantities

Use of data measured during a mission relies on the knowledge of a relation between the measured values and computed results. This is accomplished with an adequate understanding of the response function of the measurement device to predict the response from the expected particle field. Adjustments in the estimated fields from calculations are obtained by comparing predictions and actual measured results, and this will then allow improvements in radiation

environment characterizations and dose estimates. In this respect, the correction to the interior fields associated with the less known trapped radiations will be a prime target of such procedures.

5.1 Exterior Exposure Field

5.1.1 *Radiation Environment Models*

In practice, the external radiation environment in LEO is represented by various predictive models and descriptive fits. Best known are GCRs (Badhwar and O'Neill, 1992; Davis *et al.*, 2001) and their associated quiet-time geomagnetic transmission factors. Periods of geomagnetic storms provide only small corrections to the long-term averaged fields in LEO. The albedo neutrons produced by the impact of GCR with Earth's atmosphere are also well known (Korff *et al.*, 1979; Lockwood, 1972; Preszler *et al.*, 1972). GCR models are well developed and the predictive model of Badhwar and O'Neill (1992) gives a reasonable representation of the local radiation environment outside Earth's geomagnetic field. More recent descriptive fits associated with the Advanced Composition Explorer spacecraft project are now available and have the advantage of validation by measurements with high-quality instrumentation in the L1 libration point (*i.e.*, about 1.5 million kilometers from Earth in the sun's direction) where Earth and solar gravitational strengths balance each other (Davis *et al.*, 2001).

The current trapped radiation models are uncertain by a factor of two for geomagnetic quiet times and the trapped radiation experiences large fluctuations during geomagnetic storms for which there are no predictive models. In addition to the uncertainty in intensity, the trapped radiations are highly directional and their velocity vectors are constrained to lie within several degrees of a plane normal to the local geomagnetic field line. The AP-8 (Aerospace Proton Environment, Version 8) model for protons and AE-8 (Aerospace Electron Environment, Version 8) model for electrons (Vette, 1991) representing the trapped radiation environment are the basic standard, based on data obtained by NASA and Air Force measurements from 1958 to 1970. The AP-8 model includes angular dependence and both AP-8 and AE-8 provide the omnidirectional fluence estimates for geomagnetic quiet conditions in current usage.

SPEs occur mainly during times of elevated solar activity and are unpredictable in magnitude and exact time of occurrence. Their detection must rely on satellite measurements available in real-time

from some space platforms. Transmission through the geomagnetic field to LEO is normally represented by the vertical cutoff model derived transmission factors for 20 km height (Shea *et al.*, 1988) and scaled in altitude according to a magnetic dipole approximation. Recent tables of global vertical cutoff transmission factors have not been published.

5.1.2 *Spacecraft External Measurements*

External measurements can be made of the outside radiation environment to allow correction to the models to reduce the uncertainties. An ion chamber with well-defined wall thickness can serve to monitor the short-term variations in the electron environment for EVA operations and particle spectrometers provide useful data to reduce the uncertainty in the trapped particle fields and during SPEs. Recommended instrumentation is discussed in Section 6. The principal external measurements are: $\Phi_i(E,\boldsymbol{\Omega},t)$, the external fluence for particles of type i at time t with energy E moving in direction $\boldsymbol{\Omega}$; and I, the ionization current in a tissue-equivalent ion chamber.

5.2 Interior Exposure Field

5.2.1 *Shielding Models for the Space Shuttle, International Space Station, and Space Suits*

Shielding models are required for the Space Shuttle, ISS, and space suits to allow evaluation of the interior radiation environment to which the astronaut is exposed. The models consist of the distribution of materials about each field point within the vehicle and appropriate computational procedures to evaluate the interior field of transmitted particles. The internal radiation environment generally shows high directionality with large spatial gradients and varies over time with both short- and long-term temporal scales. The distribution of materials within the three structures (Space Shuttle, ISS and space suit) is represented with computer generated solid geometry models. The Space Shuttle model (Atwell *et al.*, 1989) is assumed to be made totally of aluminum alloy 2219. Higher fidelity ISS and space suit models allowing a distribution of materials are desirable.

With the exception of the absolute intensity of the trapped radiation environment and possible SPEs, the interior radiation environment can be evaluated with high-speed computational models as

has been demonstrated for Space Shuttle flight measurements (Badhwar *et al.*, 1995a; Shinn *et al.*, 1998). High-speed computational procedures allow rapid mapping of the interiors of the Space Shuttle and ISS. The computational procedures are outlined in Appendix B. Fast computational procedures for charged ions and neutrons are well developed (Clowdsley *et al.*, 2000; Cucinotta *et al.*, 1997; Wilson *et al.*, 1995). Fast computational procedures of electron and photon transport are available for limited shielding materials (Seltzer, 1980) and more general codes are still being developed. This series of electron and photon transport codes requires the approximation of shielding (including tissue) to be taken as equivalent amounts of aluminum and only provides dose, with no information on electron and photon spectra.

5.2.2 *Spacecraft Internal Measurements*

Selectively located active and passive instrumentation allows further adjustments to the evaluated internal radiation environment, thus reducing uncertainty. Particle spectrometers allow some evaluation of transmission factors and dosimetric devices allow evaluation of calculated dosimetric quantities. Both active and passive dosimetric devices are useful for evaluation of D, $D(L)$, the frequency distribution of lineal energy $[f(y)]$, and H, as discussed in Appendix A. Personal dosimeters worn by astronauts can determine some or all of these quantities in adjacent tissues.

The interior radiation environments of the Space Shuttle and ISS will be monitored by various instruments, and the measurements can be used to adjust the modeled trapped particle intensity, thereby reducing the uncertainty in estimates of the interior radiation environment. There are long-term variations depending on solar activity, which modify the environmental spectra as well as intensity, so that spectrum-sensitive instrumentation is desirable. Furthermore, active instrumentation is desirable to allow detection of time-resolved trapped and GCR components. Whatever instrumentation is used within the Space Shuttle or ISS, the instrument response needs to be accurately defined for direct comparison of measurement with predicted response as the basis for modifying the calculated results to reduce uncertainty in estimates of the interior radiation environment. The principal internal measurements are: $\Phi_i(E,\boldsymbol{\Omega},t)$

(the internal fluence for particles of type i at time t with energy E moving in direction $\boldsymbol{\Omega}$), D, $D(L)$, $f(y)$, and H.

5.3 Tissue Exposure Fields

5.3.1 *Human Shielding Models*

Shielding models for astronaut tissues are required to evaluate the fields present at specific sensitive tissues. The models consist of the distribution of the specific sensitive organs in the body and the surrounding distribution of the astronaut tissues about each point in that organ and computational models to evaluate the transmitted fields. The presence of high directionality and large spatial gradients coupled to the mobility of the astronaut poses a challenge to evaluation of the exposure fields at specific tissue points. In addition, astronaut shielding models allow the evaluation of the effect of the presence of the astronauts in the radiation environment on the local interior field and in particular on the exposure of the personal dosimeter, and on the relationships between D and H at points on the surface of the body and these quantities in deeper-lying organs. The evaluation of organ or tissue dose for the astronauts is performed with computerized anatomical models for both a male and a female (Atwell *et al.*, 1993). The models provide the distribution of tissues with relatively high fidelity. A male data set derived from computed tomography scans has also been developed but is not fully utilized in protection practice (Qualls and Boykin, 1997).

5.3.2 *Occupancy Factors*

Occupancy factors keyed to known individual activity can be used to estimate an astronaut's exposures and can be corrected by the personal dosimeter measurements. This is especially true during EVA where large fluctuations in the trapped electron environment or SPEs could greatly alter the dose gradients within the astronaut tissues. In addition, one could have a combination of shielded and unshielded TLDs in a personal dosimeter such that the shielded dosimeters did not record trapped electrons during EVA.

6. Data Collection and Interpretation for Dose Assessment

6.1 Introduction

Data collection and interpretation are essential components of an operational radiation safety program for space activities. Measurements from onboard detectors in combination with radiation transport calculations should be designed to provide sufficient information to:

- assess career exposures
- assess short-term exposures
- manage the exposures during all mission segments

There are several purposes of in-flight measurements. These include the provision of field data (fluence, dose) both integral and differential (with respect to time, LET, energy or direction, as appropriate), normalization of the calculations of the radiation field components, and, in the case of personal dosimeters, the determination of D and H. The quantities D and H refer to determinations averaged over the sensitive volume of the detector as measures of D and H to a point in the adjacent tissue.

In order to perform these functions, instrumentation must be able to accommodate the complex nature of the radiation environment in space and a range of mission profiles. Additional complications are introduced by the variety of astronaut activities both inside and outside the spacecraft.

Several types of instrumentation are required. Area monitors, fixed or portable, will be used to measure fluence and fluence rate, D and absorbed dose rate ($\dot{D}$), from which H and dose equivalent rate ($\dot{H}$) may be calculated. Due to the complex nature of the radiation field it may be necessary to differentiate fluence and D with respect to particle type and energy, LET, and direction. Active instrumentation should have a time resolution sufficient to identify temporal variations in the radiation field. These temporal variations may be associated with the characteristics of the orbit or other external factors.

Personal dosimeters can be used to make measurements of D or H to tissue at a point on the surface of the body and assign these directly to individuals. In addition, alarm or warning instruments can be used to support in-flight implementation of dose management and ALARA actions.

6.2 Dose Quantities to be Determined

The objective of the adopted dose assessment approach (Section 5) is to determine the necessary radiation protection quantities for the limitation of stochastic and deterministic effects. For stochastic effects this quantity is E determined from $E \approx \sum_{T} w_T \overline{H}_T$, where $\overline{H}_T$ is used as the surrogate for H_T (Section 2.2.2). For deterministic effects the quantity is G_T determined from $G_T = R_i D_T$, where D_T is weighted by R_i for the particle type (Section 2.2.1). Passive personal dosimeters can be used to determine D and H to a point in adjacent tissues. The quantities D_T and $\overline{H}_T$ to organs and tissues, and thus E and G_T are determined from a combination of radiation transport computations and dosimetry measurements (Section 5).

Thus, an appropriate measurement package should provide:

- input data for the radiation transport calculations. The combination of calculations and measurements will yield estimates of E and G_T;
- measurement of desired point quantities such as D, the spectrum $D(L)$, and H to adjacent tissues; and
- measurements in support of in-flight dose management and ALARA actions.

Calculations serve a dual purpose. Firstly, they are essential to mission planning in that they provide preflight estimates of the doses that would be received by the astronauts during the different phases of the proposed mission. Secondly, they are an essential component of the dose assessment process for determining the actual doses received by the astronauts during the mission. In the latter role, the calculations are combined with measurements from area and personal dosimeters in order to arrive at the final values of $\overline{H}_T$, E and G_T.

As described in Section 5 (Figure 5.1), data from the area monitors, both internal and external to the spacecraft, are used to determine essential field quantities as input to the calculations in order to define the internal radiation environment at different locations inside the space vehicle. Data from the measurement package [*i.e.,* D, $D(L)$,

and H] are then used along with the calculations to provide estimates of $\overline{H}_T$, E, and G_T. As already described, this can be achieved by using the measured D, $D(L)$, and H to normalize the computations before proceeding to compute values for each astronaut. Alternatively, the computations may provide correction factors for each astronaut to convert H values determined from personal dosimeters into $\overline{H}_T$, E and G_T values. In either approach, it is a combination of radiation transport computations and dosimetry measurements that is used to provide the ultimate values for entering into the record.

The measurement packages described in this Section have sufficient flexibility to support either approach. The proposed packages consist of:

- active devices, including TEPCs and particle spectrometers in strategic locations within the spacecraft, to collect data for short-term and career records;
- passive devices, including TLDs and PNTDs as personal dosimeters for the crew; and
- active devices to act as alerts for high transient doses and dose rates.

In this Section potential alternative, or additional, dosimetry devices that may be employed in the future are discussed, including solid-state active personal dosimeters, solid-state ionization chambers, and high-intensity electron field monitors.

6.3 Proposed Measurement Package

6.3.1 *General Discussion*

The measurement package proposed by NCRP follows naturally from the determination of the observables to be measured (Section 6.2) and the capabilities of available and planned instrumentation. No single device can determine the required dose quantities for all components of the radiation field. Since there are large variations in the magnitudes of the contributions to total D and H from the different particle types it is not generally possible to determine D or H from just one component (or components) and apply a correction factor to determine D or H for the whole field. Therefore, practical measurement and dose assessment considerations suggest the need to evaluate three main components of energy deposition, namely: (1) low-LET charged particles and photons; (2) neutrons, and protons that undergo nuclear interactions which produce high-LET secondary

particles; and (3) energetic charged nuclear fragments with $Z > 1$ (HZE particles).

The rationale for the recommended measurement package is to ensure that suitable measurements are made in each of the above three categories, that will allow determination of the dose-limit quantities, without unnecessary overlap or duplication that might result in "double counting." The choice of measurement device or devices is dictated by radiation response characteristics (particle type, particle energy, quantity to be determined), operational characteristics (direct determination of dose quantities, input to model calculations, desired accuracy, dose management, and ALARA support), as well as practical issues such as reliability, robustness and availability.

An additional important consideration is the time required for analysis of the devices compared with the duration of the mission. Long duration ISS missions may place constraints upon the frequency of analysis of passive dosimeters. If the personal measurement package on ISS does not include active dosimeters, facilities to read passive devices onboard the spacecraft may be necessary to fully implement dose management and ALARA. Such facilities may not be necessary on the Space Shuttle. Furthermore, the proposed passive personal dosimeter package is to be used both when the astronaut is inside the spacecraft and during EVA. However, supplemental passive personal dosimeters may be needed for additional locations on the astronaut during EVA because of spatial variations in the degree of shielding provided by the space suit.

The addition of TEPC (Section 6.3.2.1) to routine area dosimetric evaluation in the mid-1990s provided direct information on energy deposition in tissue by both high- and low-LET particles. The data provided are in terms of D in a small mass of tissue collected in real-time, and can be used to determine $\dot{D}$. Energy deposition events can be combined to give distributions in lineal energy (y) that are related to LET of the incident radiation. It may also be possible to use this information to estimate unrestricted LET (L_∞) distributions, which are required for determination of Q and thus H to a small mass of tissue. Radiation transport models have been used to predict y distributions measured by TEPCs (Badhwar *et al.*, 1996c; Shinn *et al.*, 1999). From these calculations estimates of the radiation environment within the space vehicle have been made. The success of this approach relies upon an accurate estimate of the external radiation field, the geometry and composition of the spacecraft, and the response of TEPC detectors to HZE particles. In general, TEPCs have little dependence of response on angle of incidence, that is, their response is approximately isotropic.

Particle spectrometers (Section 6.3.2.2) can identify particles individually by charge and energy. This is necessary information when considering radiation effects that are sensitive to particle type and fluence, as opposed to D and LET. It is also possible to make comparisons between the data and calculations. Particle spectrometers generally have limited angular acceptance and energy, and poor statistics for $Z > 2$. Details of properties and performance of both TEPCs and particle spectrometers can be found in Appendices B and C.

Thermoluminescent dosimeters (of type TLD-100® or TLD-700®) have been used routinely for both passive personal dosimeters and passive area dosimeters since the Skylab mission. In addition to TLD, high-LET passive dosimeters have been flown on almost all missions. TLDs record the energy deposited for photons, electrons, positrons, pions, protons and heavier charged particles. The response is dependent upon particle type and energy. For example, when calibrated in terms of tissue kerma to high-energy photons, TLD-100® and TLD-700® overestimate D in tissue (by several percent) for high-energy protons and begin to underestimate D in tissue for particles with LET (in water) above approximately 10 keV μm^{-1}. The underestimation has been shown to be approximately 50 percent at 100 keV μm^{-1}. However, the exact values of the over- and under-response for a given LET and particle type are not well established. The values vary from material to material and, for a given TLD material, values vary in the published literature. Furthermore, TLDs provide a single number related to D and provide limited spectroscopic information on the quality of the radiation field, *i.e.*, $D(L)$. Because of these properties, TLDs alone do not provide sufficient information to determine H. Furthermore, the design of the TLD package may introduce an unwanted dependence of response on angle of incidence. Details of TLD properties and performance can be found in Appendix C.

PNTDs have been a standard component in crew and area dosimetry packages. These detectors respond to high-LET particles, including secondary charged particles from neutron interactions, but are insensitive to photons, electrons and other charged particles with LET (in water) values less than approximately 10 keV μm^{-1}, depending upon PNTD material. Processing of PNTD can yield LET distributions for the radiation field, as well as particle type and energy. PNTDs have a strong dependence of response on angle of incidence. Details of the properties and performance of PNTDs can be found in Appendix D.

6.3.2 *Proposed Measurement Package: Active Devices*

Active devices record and display data in real-time, or near real-time. For most applications both the readout time and time resolution

are significantly shorter than the time for Space Shuttle or ISS to complete one orbit. This makes it possible to obtain measurements of rates as well as time integrated values. In most cases the time resolution is sufficient to select data from defined portions of the orbit (*e.g.*, when traversing SAA). Most active instruments can be turned on or off so as to operate in specific circumstances and conditions (EVA, SPE). Active detectors require electrical power that can be provided through connections with power supplies in the spacecraft or through batteries. They can be used as fixed or portable area monitors and devices are under development that are sufficiently small to be carried on an astronaut's person. The types and characteristics of detectors to be used in LEO should be determined by the requirements of dose assessment, as specified in Section 5. The following detectors can provide sufficient data to fulfill those recommendations.

6.3.2.1 *Tissue Equivalent Proportional Counters.* A TEPC is an active detector that is designed to measure energy deposition in volumes of tissue comparable to the dimensions of the nuclei of mammalian cells. Data are recorded on an event-by-event basis such that one can obtain a distribution of biologically relevant energy deposition events. The wall and gas cavity can be designed to make a TEPC sensitive to incident photons, neutrons and charged particles from protons to heavy ions.

When the data are integrated over the complete distribution of y, TEPCs can generate D and $\dot{D}$. The frequency distribution of lineal energy [$f(y)$] depends on characteristics of the radiation field [$\Phi_i(E,\boldsymbol{\Omega},t)$] (*i.e.*, the distribution of fluence for particle type i as a function of energy E, direction $\boldsymbol{\Omega}$, and time t) and the response of the detector. Therefore, $f(y)$ can serve as a test for radiation transport models. It can also be used to obtain D in terms of lineal energy [$D(y)$]. This is not a replicate of $D(L)$, but can be used to obtain an approximation to Q for protons and heavier particles. The detector has a large dynamic range such that it can identify signals from charged particles that deposit energy from 0.2 to 800 keV in the sensitive volume. It is also sensitive to neutrons and this contribution is also included in $D(y)$. Data from a TEPC can be displayed continuously and also stored for later transmission to the Mission Control Center.

6.3.2.2 *Solid-State Detectors.* Solid-state detectors record the energy deposited by a charged particle. The ratio of the deposited energy (dE) to the thickness of the detector (dx) yields the approximate L_∞ for the incident particle. Thus, a single detector can provide an estimate of $\Phi(L,t)$ [*i.e.*, the distribution of fluence as a function

of LET (L) and time (t)] that can be integrated to yield D and $\dot{D}$ for protons and heavier charged particles. It can be fabricated into a compact detector for use as a portable area monitor or personal dose rate meter with on-demand readout (Badhwar, 2000).

Often several of these detectors are combined to form a particle telescope that measures both energy deposition and position. When these data are combined, this detector yields a more accurate estimate of L_∞ and thus $\Phi(L,\boldsymbol{\Omega},t)$ (*i.e.*, the distribution of fluence as a function of L, $\boldsymbol{\Omega}$ and t). It can also be used to obtain $D(L)$ and Q for heavy particles, but with the restriction that the incident particles originate from a fixed direction depending on the orientation of the detector. Because of size limitations this type of detector is sensitive over a restricted solid angle ($\mathrm{d}\boldsymbol{\Omega}$).

The energy lost in one or more solid-state detectors can be used to identify the particle charge (Z) as well as the incident energy (E) to ultimately obtain $\Phi_i(\mathrm{E},\mathrm{Z},t)$ (*i.e.*, the distribution of fluence as a function of E, Z and t). Several of these detectors can be combined to point in different directions to provide a more complete description of the radiation field either outside or inside of the spacecraft.

6.3.2.3 *Active Electronic Personal Dosimeters.* There are a number of real-time electronic personal dosimeters available, mostly using silicon-based detectors (Ortega *et al*., 2001; Texier *et al*., 2001). Most of these have been designed to measure photon and beta radiation, and might be considered for the measurement of the low-LET component of the fields in spacecraft. Several have tissue-equivalent encapsulation. However, even if used only to determine the low-LET component, a full characterization of the charged-particle and neutron response is necessary before any can be recommended. Neutron and total field electronic personal dosimeters are not as fully developed as are those designed to determine photon and beta radiation fields. Direct ion storage dosimeters, described in Section 6.3.3.2, can be operated as real-time devices to determine the low-LET component.

6.3.2.4 *Active Detectors for Electrons.* Active detectors should be specially configured to measure low-LET radiations, in particular, electrons. This is normally not an issue inside the spacecraft but could be of concern during EVA, since electrons above a few hundred kiloelectron volts can penetrate the space suits. Since the trapped electron intensity can change by many orders of magnitude during and following a large magnetic storm, due to short-term perturbations of the geomagnetic field, it is recommended that an active detector sensitive to electrons be installed outside of the spacecraft

to serve as a monitor for fluctuations in the electron component of the space radiation environment for dose management during EVAs. Such a monitor could be a simple ionization chamber with a wall thickness sufficient to attenuate very low-energy electrons but thin enough to record electrons that could penetrate a space suit. The output would be the ionization current (I). Because the trapped electrons occur intermittently, it will be necessary to monitor or suppress the signal from background radiation that occurs continuously.

6.3.3 *Proposed Measurement Package: Passive Devices*

Passive devices can be used as both area and personal dosimeters. Since no single passive device is capable of dose measurement across the full spectrum of LET, measurement packages should be designed to have optimum performance in the three different regions noted above, namely: (1) low-LET charged particles and photons, (2) neutrons and protons that undergo nuclear interactions, and (3) HZE particles. Passive dosimeters currently in use on LEO Space Shuttle flights are TLDs, specifically TLD-100® or TLD-700®, to obtain D in tissue (in gray) calibrated against ^{137}Cs gamma rays. That is, the ^{137}Cs gamma-ray dose in tissue (or kerma in tissue) required to give the same thermoluminescent (TL) response in TLD as the space irradiation is reported as D in tissue at the location of the TLD detector. However, TLD-100® and TLD-700® are not the best TLD materials to use, since they have a variable and decreasing response at high-LET. Other TLD materials may be better, in that they may be more suited for use at low-LET (*i.e.*, $<$10 keV μm^{-1}) with very little sensitivity to higher-LET particles. Furthermore, since there may be a need for some passive elements to be read out frequently onboard, and others that are read only on return to Earth, the mode of readout of the luminescence dosimeters should be carefully considered. OSLDs and electronic dosimeters may be viable options. However, any new TLD or OSLD material, or new electronic dosimeters, will need to be fully characterized for the space radiation environment.

To read the high-LET component of the radiation field PNTDs can be employed. These are generally insensitive below a LET in water of approximately 10 keV μm^{-1} (depending on material) and may be employed in a mode that provides D, $D(L)$ (or D averaged over certain ranges of L), and H.

The various elements of the proposed packages are discussed below.

6.3.3.1 *Low Linear Energy Transfer Dosimetry: Thermoluminescent Dosimeters.* As noted, after calculation of the equivalent ^{137}Cs dose the TLD response needs to be corrected for the variation in the efficiency of TLD as a function of particle LET and for the neutron response of the dosimeter. This would require taking into account the best estimates of the radiation field components at an appropriate spacecraft location. Therefore, it is recommended that passive dosimetry using TLDs or OSLDs be limited to the determination of D from the low-LET charged particle and photon component only (*i.e.*, for $L < 10$ keV μm^{-1}). This can be achieved by choosing a device (a luminescence dosimeter, *i.e.*, a TLD or an OSLD) that has a minimal response to the other high-LET components. Dosimeters LiF:Mg,Cu,P (for TLD) and Al_2O_3:C (for OSLD) should be considered since they are predicted to be very sensitive to low-LET radiation, and very insensitive to high-LET radiation. This prediction is based on their gamma-ray dose response, which shows a considerably lower saturation dose for the former materials compared with, say, TLD-100®. For 5 MeV alpha particles this prediction has been shown to be true (Appendix C). Lithium fluoride (LiF) is a tissue-equivalent material for low-LET radiations and for photons. Al_2O_3:C is less tissue equivalent but still acceptable. One advantage of switching to OSLDs would be the possibility of providing small, lightweight, low-power OSL readers for the spacecraft so that the astronauts could read their own dosimeters during long-duration flights. In either case, these materials may provide excellent discrimination between low- and high-LET radiation.

As an alternative to OSLDs, one could consider radiophotoluminescence (RPL) glasses (Piesch *et al.*, 1990; 1993). Like OSLDs, these are optical-readout dosimeters, but they provide a permanent integration of the dose and cannot be re-used. Readout equipment is similar to that of OSLDs. However, like OSLDs, RPL glass dosimeters have not been tested for their response to particle radiation over a wide range of LET. Thus, before adoption of OSLDs, or RPL dosimeters, research is required to fully characterize their response in detail.

CaF_2:Tm dosimeters (such as TLD-300®) can provide useful qualitative information about the particle LET spectrum using the peak-height-ratio method (Appendix C). It has been suggested that the variation of the peak height ratio with LET for either LiF:Mg,Ti-based detectors (*e.g.*, TLD-100® or TLD-700®) or CaF_2:Tm detectors (*e.g.*, TLD-300®) could be used to provide information about the quality of the incident radiation field by calculating a "TLD average Q," namely a parameter $\overline{Q}_{TLD}$ (Appendix C). However, the variation of the peak-height-ratio with LET is nonlinear. Furthermore, it is

unclear what the obtained value of $\overline{Q}_{TLD}$ means. In general, where the radiation field has a significant neutron component, $\overline{Q}_{TLD}$ will differ from $\overline{Q}$ for tissue because of the lower neutron kerma and absorbed dose in CaF_2:Tm than in tissue. Despite claims by some authors that the $\overline{Q}_{TLD}$ value matches well the "true" average value for the low- and high-LET components, comparisons of $\overline{Q}_{TLD}$ with $\overline{Q}_D$ (D averaged Q) calculated from the TEPC data differ by as much as a factor of two. Thus, we recommend the use of CaF_2:Tm only as additional input into the model calculations and not as a quantitative method to obtain H for low- plus high-LET components.

6.3.3.2 *Direct Ion Storage Dosimeters.* In addition to personal dose rate meters discussed in Section 6.2.2.3 there are new solid-state detectors that combine an ionization chamber with a semiconductor. Specifically, the direct ion storage dosimeter is based on coupling a gas-filled ion chamber with a semiconductor nonvolatile memory cell (Wernli and Kahilainen, 2001). These are compact integrating devices that can be read out periodically and used to estimate accumulated doses over periods of several hours to at least a year.

6.3.3.3 *Neutron and High Atomic Number, High-Energy Particle Dosimetry: Plastic Nuclear Track Detectors.* To determine the neutron and HZE components, a separate device (comprising one etched track detector, or two or more such detectors of different response characteristics) should be used (see Appendix D for descriptions of methods and for references). From such a dosimeter, the point values for H in adjacent tissues can be determined. Materials that can be used are PADC/CR-39®, cellulose nitrate, and polycarbonate [Lexan (General Electric Company Corporation, New York); Makrofol® (Bayer Aktiengesellschaft Corporation, Leverkasen-Bayerwerk, Germany)]. Herein we refer to all such materials as PNTDs.

The LET (in water) threshold of PADC/CR-39® is in the range 5 to 10 keV μm^{-1}, enabling protons of energy up to about 10 MeV to be detected directly, as well as HZE particles. Secondary charged particles from nuclear interactions of higher energy protons and of neutrons, in the detector material itself or surrounding material, are also detected. Full etch track analysis of stacks of PNTDs allows the determination of HZE particle fluence and fluence rate, but is very time consuming. By a measurement of the distribution of D (fluence times LET) as a function of LET, H can be determined for energy deposition by all particles in the (approximate) LET range of 5 to 1,000 keV μm^{-1}. This can be done using single detectors, but is still time consuming. Automated analysis systems have been used but further development is needed. Another, more approximate

approach, is to use a series of different materials each of different LET threshold to obtain particle fluence in a number of LET "bins." In both approaches, although LET calibration of the detector response is in terms of LET in water, the numbers and types of secondary particles generated, for example by the neutron and higher energy proton components, will be different than those generated in tissue. Therefore, the determination of H (to tissue) will be approximate. PNTDs may also be used to estimate the higher-LET component of GCR using the simpler, less time consuming techniques developed for neutron personal dosimetry. Electrochemically etched pits are identified and counted. Readout procedures are fully automated. HZE particles will also produce an etchable track and be counted as if produced by a neutron, or neutron-like iterations of high-energy protons, and the same response factor applied (about 10 μSv per track for a typical electrochemical etch system), which will overestimate the HZE component of H. However, an additional chemical etch allows discrimination. The response of PNTDs is angle dependent and, in general, the interpretation of results requires assumptions with respect to the direction distribution of the field to which PNTDs were exposed.

6.3.3.4 *Use of Thermoluminescent Dosimeters and Plastic Nuclear Track Detectors to Estimate Effective Dose.* Measurements of H with TLDs and PNTDs located at the surface and $\overline{H}_T$ with TLDs and PNTDs located in the organs of an anthropomorphic phantom were made during a Space Shuttle mission to Mir (Yasuda *et al.*, 2000). The results indicate that the determination of H at the body surface may be able to provide an assessment of the effective dose (E) for the radiation field inside ISS. However, this conclusion needs to be supported by further investigations for other shielding configurations. The potential for developing a set of conversion coefficients that directly relate H at the surface to E for the space radiation environment, similar in concept to those used in other occupational radiation environments (ICRP, 1996; ICRU, 1998), would be worth investigating.

6.3.3.5 *Superheated Drop/Bubble Dosimeters.* Superheated drop/bubble neutron personal dosimeters are available, and have been flown on Mir and the Space Shuttle (Ing, 2001). These dosimeters respond to thermal neutrons and fast neutrons upwards from about 100 keV, but require a normalization of the neutron response to the neutron spectrum in spacecraft and corrections for proton and other ion-induced bubbles. The use of this type of device must take into account dynamic range limitations, the temperature dependence of

response or the efficiency of the correction applied for this effect, and the possibility of false readings due to microphonics.

6.3.4 *Recommendations for Measurement Packages*

6.3.4.1 *Recommendations for Area Monitoring.* Active detectors play an important role in terms of characterizing the radiation fields inside and outside of the spacecraft. Detectors with time resolutions on the order of minutes can be used to distinguish regular changes in radiation during portions of the orbit (*i.e.*, trapped radiation in polar regions and SAA, galactic cosmic rays) as well as identify other intermittent changes due to solar activity and magnetic storms.

A TEPC can provide dose and dose rate measurements with sufficient time resolution. It is sensitive to photons, protons, helium, HZE particles, and neutrons. It has the additional capability of providing information on $f(y)$ that can be used to obtain $D(y)$. Although $D(y)$ is not identical to $D(L)$, dose-averaged values of y have values very similar to those for L and thus can be used to estimate Q (Appendix A). A TEPC can be placed at fixed locations within the spacecraft or can be operated as a survey meter if necessary.

Active solid-state detectors can provide a direct measurement of particle fluence for protons and heavier particles in terms of $\Phi(L)$ (*i.e.*, the distribution of fluence as a function of L) for a single detector or $\Phi(L,\boldsymbol{\Omega})$ (*i.e.*, the distribution of fluence as a function of L and $\boldsymbol{\Omega}$) and $\Phi(\mathrm{Z,E},\boldsymbol{\Omega})$ (*i.e.*, the distribution of fluence as a function of Z, E and $\boldsymbol{\Omega}$) using multiple detectors. These data can serve as calibration points for particle transport codes used for dose assessment. When integrated, they also provide an estimate of D to silicon that can be converted to D to tissue. Because they estimate LET, they can also provide estimates of Q. Active solid-state detectors can be used as area monitors inside and outside of the spacecraft. A compact portable version has been developed and could be used as a personal dosimeter with on-demand readout.

An active detector sensitive to electrons should be installed outside of the spacecraft to serve as a monitor for fluctuations in the electron component of the space radiation environment that can change by many orders of magnitude during and following an SPE due to short-term perturbations of the geomagnetic field. This could be of serious concern during an EVA since electrons above a few hundred kiloelectron volts can penetrate the space suits. Such a monitor could be a simple ionization chamber with a wall thickness sufficient to attenuate very low-energy electrons but thin enough to record electrons that could penetrate a space suit.

The deployment of active instruments can be usefully supplemented by passive devices, for example, by PNTD stacks to determine both HZE particle fluence rates and LET distributions, and by TLDs or OSLDs to examine the spatial distribution of the low-LET component.

6.3.4.2 *Recommendations for Personal Dosimetry.* A measurement package consisting of a TLD material for measurement of the low-LET component and a PNTD stack to determine the high-LET component would appear to provide the best current solution for passive personal dosimetry in the complex radiation field experienced in space. For TLD, LiF:Mg,Cu,P would appear to be an attractive material. Alternatively, Al_2O_3:C is the best currently available OSLD material. To measure H from the high-LET components, the use of PADC/CR-39® etched track detectors is proposed. Such devices have been used as a part of the area monitoring or personal dosimeter packages on the Space Shuttle, but are not currently planned for ISS. It is recommended that they be used as personal dosimeters on both vehicles. CaF_2:Tm (*e.g.*, TLD-300®) could also be used as an adjunct personal dosimeter to provide additional information for model normalization purposes, but not for quantitative determination of dose quantities.

With this measurement package for passive personal dosimetry, H at a point in adjacent tissue is then obtained from:

$$H = D_{\mathrm{TLD/OSLD}} + \int D_{\mathrm{PNTD}}(L)\, Q(L)\, \mathrm{d}L \qquad (6.1)$$

where $D_{\mathrm{TLD/OSLD}}$ is absorded dose recorded by TLD or OSLD in the low-LET region ($L < 10$ keV μm^{-1}) for which $Q = 1$. $D_{\mathrm{PNTD}}(L)$ is the D distribution in LET determined by PNTD over the high-LET range ($L \geq 10$ keV μm^{-1}) and for which Q is dependent upon L. Correction may be needed for any overlap of the two responses so that intermediate-LET components are not double-counted.

It is recognized that this recommendation requires verification of LET dependence of the TLD response of LiF:Mg,Cu,P and of the OSLD response of Al_2O_3:C. Until such time as these data are available, therefore, LiF:Mg,Ti dosimeters (*e.g.*, TLD-100® or TLD-700®) may still be used. If so, however, this should still be along with PNTDs, as part of the passive personal dosimetry package, in order to provide LET data suitable for correcting the TLD dose response for the $L \geq 10$ keV μm^{-1} component, and for estimating H for this component from the PNTD results.

If PNTDs cannot be flown, a different approach has to be adopted. Data needs to be obtained from a TEPC or particle spectrometer used as a passive area dosimeter. If appropriate LET information

is available from the area dosimeter, then correction of the TLD response may be made by extracting (*i.e.*, from TEPC data) a dose-averaged LET ($\overline{L}_D$), from which one can evaluate a mean Q ($\overline{Q}$) from the known $Q(L)$ relationship, and an effective efficiency ($\overline{\varepsilon}$) from a measured $\varepsilon(L)$ relationship (Appendix C).

The value of H to the adjacent tissue is then approximated by:

$$H \approx \frac{\overline{Q}\, D_\gamma}{\overline{\varepsilon}}, \tag{6.2}$$

where D_γ is the dose of ^{137}Cs or ^{60}Co that is found to give the same TL response from TLD as the space irradiation. This approach suffers from the drawback that D_{TLD} for the neutron component of the fields will, in general, be significantly less than D in tissue for this component. The $\overline{Q}$ derived from TEPC measurements should be applied to D from all components to obtain the total H. The degree of approximation resulting from the adoption of the approach described will depend on the proportions of the different field components and therefore location in the spacecraft. Some new designs of passive electronic dosimeters function as small tissue equivalent ionization chambers. For these devices, an appropriate $\overline{Q}$ derived from a TEPC may be applied to determine H at a point in adjacent tissue.

Most currently available active electronic personal dosimeters are used routinely to measure low-LET radiation and have not been characterized for the types and energies of the particles comprising the fields in spacecraft. Such dosimeters, when well characterized may perform a useful role. The ideal dosimeter would be active, store integrated dose data and dose rate time profiles, and respond to all field components, allowing a good determination of $\dot{D}$ and $\dot{H}$ to adjacent tissues.

If active personal dosimeters are not used, then it may be necessary to develop onboard readout capabilities for the passive dosimeters, especially on long-duration ISS missions. Although onboard readout of PNTDs is not feasible, onboard systems for readout of TLDs, OSLDs and electronic dosimeters are certainly possible. Development in this area is therefore recommended.

6.4 Accuracy, Performance Testing, and Calibration

6.4.1 *Operational Radiation Protection Requirements on Accuracy of Dose Measurements*

6.4.1.1 *Recommendations of ICRP and ICRU.* International and national requirements, where they exist, are derived, in general,

from ICRP and ICRU recommendations. ICRP (1997) states, "In practice, it is usually possible to achieve an accuracy of about 10 percent at the 95 percent confidence level for measurements of radiation fields in good laboratory conditions. In the workplace, where the energy spectrum and orientation of the radiation field are generally not well known, the uncertainties in a measurement made with an individual dosimeter will be significantly greater. Nonuniformity and uncertain orientation of the radiation field will introduce errors in the use of standard models. The overall uncertainty at the 95 percent confidence level in the estimation of effective dose around the relevant dose limit may well be a factor of 1.5 in either direction for photons and may be substantially greater for neutrons of uncertain energy, and for electrons. Greater uncertainties are also inevitable at low levels of effective dose for all qualities of radiation." ICRU (1992) recommends, "in most cases, an overall uncertainty of one standard deviation of 30 percent should be acceptable" (instrumental error only).

6.4.1.2 *General Requirements.* The radiation exposure of astronauts is to complex, multi-component fields that are difficult to determine routinely. Nevertheless, one of the objectives of the measurement program should be to meet the general requirement for the total measurement uncertainty of the quantity being determined of a factor of 1.5 at the 95 percent confidence level. The total uncertainty in a subsequent estimate of the effective dose will be greater.

6.4.2 *Tests of Instrument and Dosimeter Performance*

There are two accreditation programs for routine personal dose measurements of external radiation, namely those of NVLAP (National Voluntary Laboratory Accreditation Program) (White *et al.*, 2001) that uses the American National Standards Institute standard (ANSI, 1993) and DOELAP (U.S. Department of Energy Laboratory Accreditation Program) (DOE, 1986). The requirements of these programs are broadly related to the recommendations of ICRP and ICRU. For both accreditation programs there is a limit on the normal incidence response characteristics determined under laboratory conditions as the sum of bias (B) and standard deviation (S). For DOELAP the criterion is: $|B| + S - |\Delta| < 0.30$, where Δ is the uncertainty of the conventionally true value of the quantity being estimated. The DOELAP test criterion is interpreted as providing approximately 70 percent confidence that a dosimeter reading would be within 30 percent of the conventionally true value.

Instruments and dosimeters used to assess doses to astronauts should meet the DOELAP or NVLAP requirements for determinations of the dependence of instrument response on energy and angle of incidence combined, plus one standard deviation, for appropriate calibration/test radiation fields. This requirement should enable the overall accuracy requirement of a factor of 1.5 to be met for actual conditions of use in fields of mixed particle types with broad energy and direction distributions.

6.4.3 *Calibration*

Calibration is the set of operations that establishes, under specified conditions, the relationship between values indicated by a measurement, and the corresponding known values of the quantity to be measured (ISO, 1993). The calibration factor (N) is the factor by which the instrument- or dosimeter-corrected reading (M) is multiplied to obtain the value of the quantity to be measured, determined under reference conditions. In the case of particle fluence (Φ) the calibration factor is given by $N = \Phi/M$. The inverse of the calibration factor is the response ($R = M/\Phi$). The response can be determined at other than reference conditions when $R = 1/kN$, where k is the field specific correction factor. The most complete calibration procedure is as part of a full type test, in which a device is exposed to a range of radiation energies and angles of incidence in a full determination of its response characteristics, as well as to other parameters which may influence its reading (*e.g.*, temperature, humidity). A full type test is extensive and time-consuming, and is therefore generally performed on only a few samples of a particular instrument or type of dosimeter to determine its overall properties.

For a laboratory calibration to be meaningful, it is necessary to clearly specify the relevant calibration conditions, including the characteristics of the reference radiation source, the irradiation facility, and the conversion coefficients used. Periodic, accurate calibrations are an essential part of any quality assurance program, as are meaningful intercomparisons. General guidance on calibration procedures is given in NCRP Report No. 112 and Report No. 127 (NCRP, 1991; 1998).

The response characteristics (ISO, 1993) of all the types of devices should be determined prior to use. In particular, the dependence of response on energy, angle, fluence/dose, and fluence/dose rate should be determined for the particle types to be measured. In addition, any interfering (influence) effects, such as those from other radiation types, temperature, vibration or electromagnetic fields, should be

determined. This will normally be accomplished by a combination of experiment and calculation. The response determinations should normally be in terms of the quantity fluence. An exception would be for the determination of photon response, for which air or tissue kerma will be more appropriate. For the determination of the response characteristics of personal dosimeters, some irradiations should be performed on either an anthropomorphic phantom or a surrogate. Sufficient data should be available to estimate dependence of response on angle of incidence. Where needed and where available, recommended fluence to D and fluence to H conversion coefficients should be used.

The statistical uncertainty of laboratory calibrations is commonly far less than the above uncertainties. However, the D and H response of devices is frequently appreciably energy- and angle-dependent. In order to assess whether the above requirements on total uncertainty can be achieved in practical measurements, either determination of the response is required for the radiation field in which it is to be used, or in a simulation of this field, or it should be possible to calculate the response in this field from the knowledge of the field and of the detailed energy- and angle-dependence of response of the device.

Response data for the types of devices to be used should be determined for the following energy ranges as appropriate: protons from 10 to 800 MeV; HZE ions (*e.g.,* helium, carbon, silicon, iron) from 50 MeV n^{-1} to 1 GeV n^{-1}; electrons from 0.5 to 10 MeV; and neutrons from 1 to 180 MeV, monoenergetic or quasi-monoenergetic, plus response data for fields which replicate the neutron field produced by the interactions of GCR with shielding material.

7. Role of Biodosimetry in Dose Assessment

Biodosimetry is the use of a biological marker for assessing the magnitude of an exposure to radiations or chemicals. The unique contribution of a biodosimetry program is that it provides an individual's dose assessment as estimated from a biological endpoint. Thus, it includes the response to the cumulative exposure and allows for an assessment of variations in individual sensitivity.

A number of different biological markers have been utilized for assessing ionizing radiation exposures with the most frequent being genetic alterations, such as chromosomal aberrations and gene mutations, and electron spin resonance in teeth and fingernails, for example. These methods have been employed for dose estimation for a wide range of accidental exposures and in occupational settings, generally with a good level of success. However, there are challenges associated with biological dosimetry for astronauts that were not addressed in these previous studies, specifically calibration for the unique radiation qualities and dose distributions encountered in space.

The choice of method depends upon the specific exposure scenarios being estimated, namely, duration of exposure and whether it is fractionated, together with time of sampling in relation to exposure, number of individuals involved and speed with which results can be obtained. In the following discussion particular attention is given to the aspect of how readily exposure assessment could be made while the astronauts are still in space. Several methods are discussed in the following sections.

7.1 Electron Spin Resonance

The use of electron spin resonance with teeth or fingernails is problematic given that there is little information on its application with high-LET radiations and nonuniform exposures. Furthermore, the equipment necessary for the analysis would not be available until the return to Earth. Thus, its use would be restricted to longer-term evaluation.

Recent intercomparisons on coded samples of artificially irradiated whole teeth indicate that with certain methodologies doses of about 100 mGy can be accurately measured (Egersdorfer *et al.*, 1996). However, for the same studies, a high degree of variability in accuracy between laboratories and for different methods was observed.

7.2 Biochemical Indicators

As noted by Muller and Streffer (1991), the use of changes in the chemical composition of body fluids (saliva, blood, urine) for the estimation of radiation dose is an attractive idea. Following radiation exposure, there is a release of enzymes or degradation of proteins and nucleic acids, leading to shifts in the concentration of a number of substances, *e.g.*, amylase, taurine, thymidine, deoxycytidine (Kaul *et al.*, 1986). The apparent attractiveness of this approach is outweighed by the fact that there is a high variability, within and between individuals, of the concentration of the molecule being studied. None of the biochemical indicators that have been described have been (or can be) used as a quantitative dosimeter. Thus, no lower level of detection can be established for these markers.

7.3 Erythrocytes with Transferrin Receptors

A recently described approach (Gong *et al.*, 1999) utilizes the prolonged life span of erythrocytes bearing transferrin receptors on their membrane as a proposed dosimeter. The authors describe a logarithmic-quadratic dose response over a 1 mGy to 1.5 Gy x-ray range. At this time the approach has only been tested in rats, and only with x rays. A number of assay parameters and the range of interindividual variation need to be more clearly delineated. In addition, the assay, as described in rats, is conducted some six weeks after exposure to allow for the prolonged life-span phenotype to develop. This assay cannot be recommended for use on astronauts exposed to high-LET radiations in space. This method has not been applied to humans thus no lower limit of detection has been established.

7.4 Gene Mutation Assays

The gene mutation assay that would appear to have the greatest potential for the assessment of exposures to ionizing radiations

would be that of glycophorin A mutations (Bigbee *et al.*, 1997). The method is rapid, relatively easy to conduct, and relatively sensitive. The drawbacks are that there is very little experience with the use of the assay for high-LET exposures. In addition, the nonuniform nature of the exposure would be detrimental to the use of the assay as a whole-body dosimeter.

While the assessment of low level of detection for the glycophorin A assay has been studied in a limited way, the study of Tucker *et al.* (1997) for radiation workers at the Sellafield Nuclear Facility indicated that no increase in variant frequency was observed up to an effective dose of 1.1 Sv, with the majority of individuals having >500 mSv, the lower detection level. In contrast, the frequency of stable chromosomal translocations assessed by fluorescence *in situ* hybridization (FISH) increased with dose over this range for the same individuals. An additional note is that these exposures were chronic.

7.5 Cytogenetic Alterations

7.5.1 *Micronuclei*

Micronuclei result from loss of whole chromosomes or acentric chromosome fragments from daughter nuclei following cell division. They appear as small, membrane-bounded inclusions in the cytoplasm. Their assessment is relatively easy and rapid. The frequency of micronuclei has been used for estimating exposures for a number of radiation accidents with reasonable agreement with physical estimates. The drawbacks are that few studies have been conducted with high-LET exposures, and the assay is not reliable for partial body exposures. In addition, the sensitivity is marginal at low exposure levels. Thus, the micronucleus assay would not be suitable as a biodosimeter in astronauts exposed to space radiations.

The incorporation of the cytochalasin B technique, whereby cells in their second post-exposure cycle can be specifically analyzed for micronuclei, has greatly increased the sensitivity of the assay. If individual pre-exposure levels of micronucleus frequency are available, an absorbed dose of 50 mGy can be detected; without knowledge of this background frequency the level of detection is estimated to be 100 mGy (Prosser *et al.*, 1988).

7.5.2 *Acentric Fragments in Prematurely Condensed Chromosomes*

Interphase chromosomes can be prematurely condensed to be observable microscopically either by fusion with mitotic cells by treatment with a phosphatase inhibitor (okadaic acid) and a protein kinase ($p34^{cdc2}$/cyclinB) (Prasanna *et al.*, 2000), or using calyculin A (Kawata *et al.*, 2000). Structural and numerical chromosomal alterations can be observed as an increase (or decrease) in centric chromosome number or from the presence of acentric fragments. The method has been used in a laboratory setting to assess exposure to x and gamma rays (Kawata *et al.*, 2000; Prasanna *et al.*, 2000) and several high-LET radiations (Kawata *et al.*, 2000). The advantages are that nondividing cells can be used for assay and the analysis is quite straightforward. The current drawback is that the assay has had no application as a true biodosimeter, and issues such as responsiveness to partial body exposures or chronic exposures have not been addressed. Further investigation appears warranted for assessing the value of prematurely condensed chromosomes (PCC) as a biodosimeter in the space radiation environment.

The fact that this PCC method has not been used in biodosimetry means that a lower detection level has not been established. A reasonable assumption is that it will be no more sensitive than other cytogenetic methods, given similar cell numbers analyzed. The advantage is that by analyzing interphase cells a larger number of cells are available for analysis.

7.5.3 *Chromosomal Aberrations*

The method that has been used the most extensively for radiation biodosimetry is that of the analysis of structural chromosome alterations. The most recent incorporation of FISH techniques has allowed for the assessment of symmetrical (transmissible) translocations. This allows for fairly reliable dose estimation at long times after exposure. Chromosome aberration dosimetry has been successfully applied to radiation accident victims, atomic-bomb survivors, and a wide range of occupationally and medically exposed persons. These scenarios include chronic exposures and partial body exposures for which specific methods have been developed to aid in exposure estimation. The distribution of aberrations among cells is useful in this regard. Even with this strong record of success, the application of the method for dosimetry in astronauts in space has significant drawbacks as evidenced by published studies (reviewed in Testard

and Sabatier, 1999). The major problems are interindividual variations in response and the nature of the exposures by which only a small number of cells will actually be hit. This latter concern is accentuated when the consequence of a hit by a high-energy particle is taken into account; such a cell might well be so damaged that it will not contribute to the analyzed cell population.

Additional laboratory investigation is required in order to consider using cytogenetic analysis as a reliable dosimeter for space flights. The problem will remain that analysis is technically demanding and time consuming.

The lower level of dose detection using chromosomal aberrations is dependent upon the number of cells analyzed. This point is addressed by Bauchinger (1995) who estimates that for 5,000 cells analyzed (using a generalized background frequency for dicentrics) a significant increase in dicentrics should be observed at about 100 mGy for a group of individuals. Twenty thousand cells would need to be analyzed to detect 50 mGy. Knowledge of the pre-exposure dicentric frequency can lower this detection level without increasing the number of cells analyzed.

The study by Tucker *et al.* (1997) reports a lower detection level of about 500 mSv effective dose for occupationally exposed individuals using FISH analysis of stable aberrations. The exposure was chronic in this case; a situation for which this type of translocation analysis is particularly applicable. Again, the sensitivity of the assay would be increased by having available the pre-exposure aberrations frequency.

7.6 Summary for Methods

Based upon the specific requirements for a biological dosimeter for assessing radiation exposure to astronauts in space, namely high-LET exposures, highly nonuniform exposure, ease of analysis, and rapidity of obtaining reliable dose estimates, it is proposed that a version of the premature chromosome condensation method or FISH analysis of metaphase cells are the most likely to be viable. Additional laboratory research is needed for both to validate their utility for the stated purpose.

7.7 Current NASA (Lyndon B. Johnson Space Center) Methods

Until fairly recently, JSC used the conventional cytogenetic method for biodosimetry for astronauts. The approach, still used

by many surveillance laboratories, is to assess the frequencies of chromosomal dicentrics in Giemsa-stained metaphase preparations and estimate dose using standard dose-response curves developed from *in vitro* exposures of human lymphocytes. Most of the published literature on estimated doses for astronauts was obtained utilizing this method. Recently, JSC has begun to use the assessment of chromosomal translocations in metaphase by FISH for estimating radiation exposures to astronauts from extended periods in space (Yang *et al.*, 1997). The FISH method used involves chromosome painting with probes for pairwise combinations of chromosomes 1, 2 and 4 or simultaneous use of all three probes. The use of all three probes allows for assessment of about 24 percent of the genome. As with the conventional method, dose estimation is achieved by utilizing standard translocation calibration curves from *in vitro* exposure of human lymphocytes. The difficulty of this method is how to handle mixed radiation exposures. The current approach is to use the x- or gamma-ray combined calibration curve (or gamma-ray curve) that uses preflight blood samples from all astronauts on a particular mission taken three months or less prior to flight. The postflight samples are typically obtained within two weeks of return. The blood samples are grown in culture for 48 h after mitogenic stimulation, at which time metaphase cell preparations are produced.

The sensitivity of this approach has been tested only to a limited extent. As an example, the analysis of blood samples from six crewmembers gave in-flight estimates of 0, 90, 180, 210, 210 or 270 mGy of equivalent gamma-ray absorbed dose to the whole body. In general, based upon the usual number of cells analyzed (about 4,000) the sensitivity would allow for the detection of 50 mGy and higher. The analysis of more cells would clearly increase the sensitivity. It is also proposed by JSC to use gamma-ray calibration curves obtained for each individual for use in postflight dose estimation for that particular individual. This approach takes into account individual variations in radiation sensitivity, and the fact that background translocation frequencies vary quite considerably among individuals.

7.8 Recommendations and Future Considerations

Use of the FISH method as described in Section 7.7 is the most appropriate biodosimetry approach for astronauts based upon available knowledge, technical availability, and experience. JSC is collecting PCC preparations with the aim of determining if their use might be advantageous, particularly to alleviate the need for obtaining

metaphase preparations using *in vitro* culture (see Kawata *et al.*, 2000 for description of methods).

NASA should continue to use biodosimetry as an ancillary component of radiation dose assessment for astronauts during extended space flights. The current JSC approach of using FISH for analyzing stable chromosomal translocations in peripheral lymphocytes both in pre- and postflight samples appears to be providing useful information on exposures. The establishment of calibration curves from individual preflight blood samples increases the sensitivity. Incorporating analysis of PCC will provide larger analyzable cell samples. Improvements that can be envisaged are using chromosome painting probes and computer analysis that allow for assessment of translocations in all chromosomes at the same time. This method has been used successfully for tumor analysis. Automating the various FISH methods will increase throughput enormously.

The area of genomics or molecular profiling is receiving considerable attention as an approach for assessing perturbations in gene or protein expression at the total cell level. Ongoing studies in a number of laboratories are beginning to describe alterations in gene expression patterns after radiation exposures over a broad dose range (*e.g.*, Amundson *et al.*, 2000). Specific gene expression patterns could be used as biodosimeters once genes have been identified whose expression remains elevated or decreased for extended periods of time. An automated analysis of specifically constructed gene arrays is quite feasible.

The rapid enhancement of technologies for measuring changes in cellular markers (in response to radiation) will mean that new biodosimeters will be developed that will be anticipated to detect very specific exposures, *i.e.*, cellular fingerprints.

8. Recommended Management of Astronaut Radiation Safety Program

While a team of experts at the Mission Control Center directs radiation protection actions for astronauts by means of flight rules (Section 3.1), the overall concept for a radiation protection program for astronauts is essentially the same as for other radiation workers. Dose management and ALARA program recommendations established for other types of radiation workers can provide NASA management useful guidance in setting up an effective operational radiation safety program (NCRP, 1990; 1994; 1998; 1999). Specific recommendations for the program are provided in this Section.

8.1 Components of a Low-Earth Orbit Operational Radiation Safety Program

The main components of an operational radiation safety program designed to implement the principles of dose limitation and ALARA for astronauts working in LEO are:

- to facilitate actions, both in advance of a mission and in-flight, that respond to space radiation conditions or mission decisions that significantly affect the level of radiation exposure to the astronauts, and radiation protection decisions that significantly influence conduct of the mission;
- to collect and record data to assess astronaut doses for individual mission and cumulative career records; and
- to identify, plan and carry out practical ALARA actions to avoid unnecessary levels of radiation exposure.

NASA management should implement and maintain an effective radiation safety program with the following features: clear definition of the goals of the program, statement of the organization's commitment to the application of the ALARA principle, statement of management's commitment to provide adequate budgetary support for the program, and periodic review of the overall program effectiveness.

The radiation safety program organizational structure and lines of authority should be clearly delineated and easily understood by all individuals having radiation safety responsibilities in the program. In particular, the radiation safety roles and responsibilities of the flight director, flight surgeon, RHO, and SRAG, for both individual flights and for the overall program, should be clearly delineated.

This Report provides several recommendations for improvements in monitoring and controlling radiation dose to astronauts. With an effective operational radiation safety program, individuals within NASA will be able to identify the individual or group to whom they could go to ensure that implementation of a proposed ALARA action would be considered. Responsibility should be clearly assigned for ensuring the translation of radiation protection strategies and instrumentation from design and development through engineering, preparation for flight, and in-orbit use.

8.2 Radiation Protection Principles Applied to Low-Earth Orbit Missions

As with all radiation workers, the following principles of radiation protection apply to astronauts during LEO missions (NCRP, 1993; 2000a):

- any activity that involves radiation exposure must be justified on the basis that the expected benefits to society exceed the overall societal cost (justification);
- the total societal detriment from such justifiable activities or practices is to be maintained ALARA, economic and social factors being taken into account; and
- individual dose limits are applied to ensure that the principles of justification and ALARA are not applied in a manner that would result in individuals or groups of individuals exceeding levels of acceptable risk (limitation).

Radiation exposure from space flight is justified by the fact that it is an environmental reality associated with the exploration of space. The dose limits established for astronauts (NCRP, 2000a) reflect the importance given space explorations and the limited and closely monitored population of astronauts. These two principles of radiation protection (the first and third items above) are already factored into the overall protection efforts provided for the astronauts who are subject to multiple high-risk activities.

The sources of exposure that should be included in NCRP dose limits for astronauts and the actions that constitute an appropriate approach to immediate dose management and ALARA during LEO missions are the subject of this Section. In this Report, "immediate dose management" refers to actions taken to address the potential for high doses that result from transient events in the space radiation environment that could impact the conduct or completion of the mission or mission tasks, and ALARA refers to actions taken to keep all doses as low as reasonably achievable by balancing the mission objectives with practical dose reduction steps.

8.3 Sources of Exposure Included in NCRP Dose Limits for Astronauts

The dose limits for astronauts include the cumulative dose from space flight, the dose associated with mission-related aviation activities (excluding commercial flights), the dose from biomedical research conducted as part of the astronaut's mission duties, and any other occupational doses including any received prior to work as an astronaut. The dose limits do not include normal background radiation on Earth or radiation dose received from diagnostic and therapeutic medical procedures conducted as part of the astronaut's overall health care.

Astronauts perform significant noncommercial aviation activities as part of their training for space missions, and the doses from such activities should be included in the cumulative career dose for stochastic effects. The doses can be estimated based on total flight time and average dose rate for the given activity, unless specific measured data are available.

Dose from mission-related biomedical research prior to, during or after a given mission should be included in the cumulative career dose for stochastic effects because the dose is a consequence of participation in that mission. Radiation doses from diagnostic and therapeutic medical procedures should not be included in the career dose because they have personal benefit in assessing or improving the astronaut's health. In addition, previous medical radiation doses, from diagnostic or therapeutic medical procedures, are assumed to have provided the individual a greater benefit than the risk associated with the doses and should not be used in determining qualification for future occupational exposure. In some cases, it may be difficult to distinguish biomedical research from standard medical care for an astronaut. Determination of which activities are biomedical research

and which are not is made by the Institutional Review Board governing astronaut activities.

8.4 Immediate Dose Management and Basic "As Low As Reasonably Achievable" Concepts

While there are many differences in the way astronauts receive their radiation exposure from that of a typical radiation worker, the basic concepts of radiation protection remain the same. Radiation protection actions based on time and shielding may be utilized in unique ways to maintain radiation exposure below the administrative levels (Section 3.1) and the dose limits, and these actions also can be used effectively in maintaining the astronaut's radiation exposure ALARA. Specific in-flight radiation protection actions must be based on real-time information of space radiation environments and on effective communication of this information to the flight control team. Good decisions on radiation protection actions require training and understanding of radiation fields by astronauts, by the entire flight control team, and by the entire flight management and design team. As in conventional radiation protection programs, decisions to take action to avoid radiation exposure of an astronaut are easily identified when they are related directly to preventing a person from reaching an administrative level or a dose limit. The recognition and decision to take specific action to maintain radiation doses ALARA are based on the organization's commitment to continually assess reasonable steps that can be taken to reduce doses. Thus, established radiation protection and ALARA program models, philosophies and lessons learned can be used to further enhance radiation safety programs for astronauts.

Preplanning (*i.e.*, engineering design and mission planning) and the modification of activities in-flight are important components of the radiation safety program. Occasionally, it may be necessary to modify astronaut activities quickly to keep doses below administrative levels or dose limits (immediate dose management). The ability to predict the space radiation environs and to measure space radiation levels in real-time are paramount to implementing immediate dose management and ALARA actions.

Immediate dose management and ALARA actions may differ between Space Shuttle missions and for ISS missions. In spite of these differences, actions to reduce radiation exposure comprise a continuum of effort to keep astronaut doses below dose limits, administrative levels, or ALARA. Longer ISS missions may result in a

considerably higher dose to the astronaut. However, ISS mission objectives may allow more flexibility in the timing of certain procedures, like an EVA, to avoid a high-dose environment.

8.4.1 *Immediate Dose Management Issues*

To be effective, immediate dose management in the NASA team environment requires all individuals involved to understand the resources available and their individual responsibilities with respect to corresponding actions, and to establish effective lines of communication. Implementation of immediate dose management actions is the responsibility of all team members involved with work impacting the astronaut's exposure to radiation. As soon as it is recognized that a specific activity, *e.g.*, an extended EVA, may cause an astronaut to exceed the administrative level or the dose limit, action should be considered to amend or terminate the activity. A written plan, notably the flight rules mechanism (Section 3.1), should contain the implementing procedures.

8.4.2 *Basic "As Low As Reasonably Achievable" Concepts*

An effective ALARA program depends on everyone involved in design and management of spacecraft and missions understanding the space radiation environment and its impact on astronaut radiation exposure.

The RHO should assess the opportunities to apply ALARA. All levels of management should be involved in establishing the objectives of the program to stimulate interest and involvement and to foster "ownership" in activities. Real-time data on the radiation environment during a flight are essential for the management team. Postflight review of exposure data and assessment of actions taken are necessary to provide the management team with feedback on the effectiveness of their actions. The ALARA program should be supported by senior management and should be reviewed periodically to determine its effectiveness.

8.4.3 *Considerations for Spacecraft and Space Suit Design*

The need for immediate dose management and ALARA actions should be actively considered when designing or modifying the Space Shuttle, ISS, and EVA suits.

The placement of radiation instruments should be chosen to provide the best real-time information on astronaut radiation exposure (Section 6). Immediate dose management includes providing areas where astronauts could be moved (*i.e.*, to a safe haven providing additional shielding, and/or by repositioning of the Space Shuttle), and in the case of extreme exposures providing for emergency return of the astronaut. To minimize career doses, optimized shielding should be provided for those areas of higher occupancy, such as areas used during off-duty hours and sleeping quarters. For example, model calculations and ground-based testing indicate that hydrogenous compounds are most effective at attenuating GCR radiation. Polyethylene (CH_2) is lightweight, safe and simple to install, and has recently been added to some of the sleeping quarters onboard ISS.[10]

8.4.4 *Considerations for Preflight Planning*

Once again, the historical information on space radiation environments and information on projected radiation doses are necessary in assessing the mission plan and its impact on astronaut exposures.

Choice of the flight path has significant impact on both immediate dose management and ALARA. Some choice may be available in the altitude, attitude, time and duration of the flight to affect exposures. In planning EVAs, choice may be available in the timing and duration. Full utilization of the design features should be incorporated into the in-flight procedures at the preflight planning stage.

8.4.5 *Considerations for Continuous In-Flight Review*

During flights, changes can occur in the mission plan, as well as in the space radiation environment, which can affect an astronaut's exposure or potential exposure. As with any management of exposure control, the level of effort to identify dose reduction strategies, the involvement of management review and the immediacy of action increase as higher doses are anticipated. Astronauts have important responsibilities in their own dose management during flights. They are responsible for wearing the assigned dosimeters, for taking the necessary radiation measurements, and for taking the directed actions.

[10] Cucinotta, F.A. (2001). Personal communication (Lyndon B. Johnson Space Center, National Aeronautics and Space Administration, Houston, Texas).

A model for immediate dose management and ALARA assessment by astronauts and mission control during LEO flights may be as follows:

- As the mission progresses, continually identify and assess reasonable opportunities to reduce astronaut doses even if the administrative levels are not being approached (ALARA action).
- If the astronaut's dose is anticipated to exceed a pre-established administrative level for the mission, an assessment should be made of actions to reduce further dose or to prevent the anticipated dose from being received (immediate dose management action).
- If the astronaut's dose is anticipated to exceed the cumulative short-term or career limit, an immediate assessment, including consideration of ending the mission for this astronaut, should be made to reduce additional dose or to prevent the anticipated dose from exceeding the short-term or career limit (immediate dose management action).
- If an astronaut has received greater than the cumulative short-term or career limit, then the mission should end for that astronaut as soon as practical (immediate dose management action).

8.4.6 *Considerations for Postflight Review*

The dose placed in the record for an astronaut from a given mission may not be known fully until after completion of the mission. Some of the radiation measuring devices used are passive devices, requiring processing upon return to Earth. Some data gathered may not be sent back to Earth during the mission, but stored electronically. Upon return to Earth, these data need to be processed to provide the final dosimetry record.

The final dose should be determined as soon as possible following the mission and that information reviewed with the astronaut. These actions should be completed before the astronaut's next mission or within three months, whichever is sooner.

A review should be made of the immediate dose management and ALARA actions associated with the mission. The review should be taken into account when determining the need for changes in design criteria, preflight planning, and flight rules used for future flights.

8.5 Radiation Safety Training for NASA Personnel

An NCRP symposium (NCRP, 1997) identified "a universal need to educate those involved in applying radiation dose limits to ensure

that they understand that the limits are not there to 'be used up'; rather their purpose is to serve as a constraint on operation and as a guide for the design of the associated radiation protection systems." All NASA personnel whose work has impact on astronaut exposure to radiation should be trained in the techniques of radiation protection, with emphasis on implementation of immediate dose management and ALARA. The scope and depth of this training should be related to the corresponding level of impact the individual may have on astronaut dose.

8.5.1 *Astronauts*

Astronaut training concerning radiation is described in NASA (2000c) for Space Shuttle crew and NASA (2000d) for ISS crew.

Astronauts currently receive radiation training at various times throughout their career. During the astronaut candidate year they receive a 1 h overview of the JSC Space Flight Radiation Program. When training for a specific flight, Space Shuttle astronauts are instructed on use of the radiation monitoring equipment, and in the course of this discussion, they receive a refresher on the radiation environment. ISS crewmembers receive the same training as Space Shuttle crewmembers, but also receive more detailed information on their projected dose, and the implications and possible health consequences of this exposure.

Ten days before the flight, during the medical exam, crewmembers are advised of the projected exposures and associated risks of both in cabin and EVA exposure. They are also reminded to wear their personal dosimeters throughout the mission. Space Shuttle crewmembers receive approximately 30 min of radiation training in the preflight period. ISS crewmembers receive 2.5 h of radiation training prior to flight. The dose received is communicated to the astronaut during a postflight debrief.

The astronaut's radiation protection training should focus on the following:

- biological risks of radiation exposure, particularly for the high-LET space radiations
- measurement of radiation and dose
- operation of and proper wearing of personal radiation measuring devices
- techniques an astronaut can use to reduce dose in-flight
- specialized training specific to a given mission, such as operation and maintenance of an area radiation monitor

- procedures and administrative controls including dose limits and the flight rules (immediate dose management and ALARA)
- terminology associated with dose management activities to ensure effective communications
- NASA's operational radiation safety program and how ALARA actions are proposed and implemented
- review of actual events, especially those involving high transient doses

8.5.2 *Flight Directors*

Flight director training concerning radiation is described in the *Flight Director Certification Guide* (NASA, 1998). The flight director is the individual responsible for a given mission. The current radiation safety training for flight directors consists of an introductory briefing at the start of their overall training, which includes radiation protection terminology, description of the space radiation, radiation risk versus dose, dose limits, and the ALARA philosophy. Beyond this briefing, they generally receive little formal training in radiation issues. Occasionally a special briefing is provided when there are significant changes or significant updates to the flight rules. Most training is informal, but can be substantial, occurring during development of radiation flight rules and in the course of mission planning, mission simulation, and flight training.

Like managers and supervisors of other radiation workers, the flight directors should receive radiation protection training that parallels those they supervise, but not necessarily to the same depth. The flight director's radiation protection training should focus on the following areas:

- policies and procedures affecting astronaut's radiation dose
- implementation of immediate dose management and ALARA actions and their importance
- interfaces of different NASA groups so that they are able to identify and resolve conflicts in coordinating radiation protection activities
- terminology associated with dose management activities to ensure effective communications
- NASA's operational radiation safety program and how ALARA actions are proposed and implemented
- review of actual events, especially those involving high transient doses and those involving the actions of a flight director

8.5.3 *Flight Surgeons*

Flight surgeon training concerning radiation is described in the *ISS Crew Surgeon Training Certification Plan* (NASA, 1999).

A flight surgeon is assigned to each mission and is responsible for that crew's health and safety. The current radiation safety training for flight surgeons consists of an initial 3 to 4 h of training in radiation issues, including the ALARA principle. The RHO provides quarterly briefings to the flight surgeons as refresher training and to keep them informed of changes and new radiation issues and concerns. In the course of their duties flight surgeons may receive substantial informal training as part of the team that is responsible for crew health and safety. They also receive informal training through involvement in mission planning and as participants in a variety of activities that address radiation issues.

As with the flight directors, the flight surgeon should receive radiation protection training that parallels those of the astronauts, and particularly in regard to health effects. The flight surgeon's radiation protection training should focus on the following areas:

- biological risks of radiation exposure, particularly for the high-LET space radiations
- procedures and administrative controls including dose limits and flight rules (immediate dose management and ALARA)
- implementation of immediate dose management and ALARA actions, and their importance
- interfaces of different NASA groups so that they are able to identify and resolve conflicts regarding health consequences of ongoing or projected radiation doses
- terminology associated with dose management activities to ensure effective communications
- NASA's operational radiation safety program and how ALARA actions are proposed and implemented
- review of actual events, especially those involving high transient doses and those involving the actions of a flight surgeon

8.5.4 *Radiation Health Officer and Radiation Safety Support Groups*

The RHO and individuals in the radiation safety support groups should have training equivalent to radiation protection professionals in other professions who are assigned equivalent types of radiation safety duties (NCRP, 1998; 2000b). Radiation protection training must also be specific to the special circumstances of the space radiation

environment. They should also have training on the specifics of NASA's operational radiation safety program for LEO.

8.5.5 *Other Supporting Specialists*

Other individuals whose work can affect the astronaut's radiation exposure should have radiation safety training that is commensurate with the level of effect their work might have on astronaut dose. Among these individuals are engineers, designers and mission planners. These individuals' radiation protection training should focus on developing the following knowledge:

- how their work can affect astronaut dose
- what the immediate dose management and ALARA concepts are, and how they can help implement them
- NASA's operational radiation safety program and how ALARA actions are proposed and implemented
- review of actual events, especially those involving high transient doses and those involving the actions of individuals with similar work responsibilities

9. Radiation Safety Records

The principal reason for keeping radiation safety records is protection of the astronauts. This Section describes the elements of a program for operational radiation safety records, but does not prescribe a particular methodology for construction or maintenance of the records.

In this Report the terms "dosimetry records" and "radiation safety records" are used. Dosimetry records are the collections of information that document the radiation doses that astronauts receive from space flight, mission-related aviation activities, mission-related biomedical research, and previous occupational work. The dosimetry records contain, or are linked to, all the basic information that is necessary to obtain the radiation doses, *e.g.*, the personal dosimetry measurement package (Section 6.3). Radiation safety records are the broader collections of information that relate to radiation exposure of the astronauts. The radiation safety records consist of multiple sources of information that are linked (*i.e.*, the dosimetry records and their supporting data and files, and other information that bears on the radiation exposure of astronauts). When the term "records" is used, the meaning is general.

The objectives of the overall radiation safety record-keeping program are to:

- aid in the protection of astronauts
- evaluate the effectiveness of radiation protection programs
- advance the collection of data that are accurate, reliable, confidential, and retrievable
- provide a uniform set of records

Dosimetry records for each astronaut should be kept in a manner to satisfy the following purposes:

- inform astronauts of their mission and cumulative radiation doses
- make decisions on crew selection and mission planning
- provide information for making decisions about the flight plan
- evaluate the operational radiation safety program to ensure effective program operation
- demonstrate compliance with administrative levels and dose limits

- provide reliable data for epidemiological studies
- provide information for making or contesting claims for radiation-induced injury

All records should be maintained in accordance with the highest standards of record keeping (ANSI, 1999; Fienberg *et al.*, 1985; NCRP, 1992) and should be legible, accurate, reliable and interpretable. Individuals who maintain the records should be diligent in protecting the identity of astronauts and any proprietary information. Information that may be separate from the dosimetry records, but which is important to interpret doses or recalculate dose quantities, should be linked in a manner that assures all information will be available for future interpretations or recalculations.

Records may take the form of hard copy, microform, or computer readable media. Each form has its own strengths and limitations and may be used for different purposes. Of particular importance is the conversion of old data to new formats when changes in computer hardware render old formats unreadable. Records should be stored in a durable enough manner to limit the risk of loss from theft, fire and water damage. A listing of content and location of records should be maintained to facilitate their retrieval.

When data are stored on computer readable media, the original or reproduced records from which the computer records were derived should be maintained separately to help interpret ambiguous computer data and to verify computer records if they become damaged or unreadable. To enhance reliability, computer records should be backed up on a regular basis.

9.1 Content of Records

Standard operating procedures should be written to enable those responsible for generation and maintenance of the records to document and retrieve information in a timely and reliable manner. Procedures should address the indexing, linkage and storage of documents. Standard codes and coding conventions should be used, *e.g.*, North American Industry Classification System (OMB, 1997) and Standard Occupational Classifications Manual (OMB, 2000).

Information should be documented in as specific or quantitative a form as is available. However, qualitative information should also be kept when it may be useful for interpretation of the records or recalculation of radiation doses. When quantities are derived or calculated from measured quantities, both the measurement data and the quantities derived from them, along with references to the

method used in the derivation should be maintained along with all information that may be useful in the interpretation of the measurement data. Missing information should be addressed in the records, and data that were estimated or calculated rather than measured directly should be documented. The records should contain adequate information to facilitate the interpretation of an empty field or zero value. Computations and estimates should be supported by records that provide the method used to perform the calculation or to make the estimate.

Dosimetry records and associated reports should include calendar dates of radiation exposures and starting and stopping dates for radiation monitoring as well as the date the records were generated. These records should include the magnitude and dates of radiation exposure and linkage to other records that identify the sources of exposure, place where the exposure occurred, description of radiation fields, description of physical factors that may alter the field, and information about other potentially harmful exposures.

The dosimetry records should contain sufficient information to permit unique identification of the individuals involved and information on job or task assignments that should be updated at least annually. Information on general work location (*e.g.*, Space Shuttle, ISS, EVA) should be linked to the dosimetry records to facilitate correlation analysis. Other information, such as non-mission related diagnostic and therapeutic medical radiation exposures, should be linked to the dosimetry records, but the radiation doses from the medical procedures should not be added to occupational doses either for planning purposes or to limit occupational exposure. Medical radiation exposures should be maintained in the medical department.

Information important to standard methodology, collection of data, or calculation of radiation doses may exist in other files that are separate from the dosimetry records. These files should be linked to the dosimetry records in a manner that facilitates re-evaluation and auditing of astronaut radiation doses. Files to be kept in or linked to the dosimetry records include:

- standard operating procedures on how to maintain the record
- standard operating procedures on how to compute the radiation dose of record
- personal data for each astronaut, *e.g.*, age, sex, height and weight
- flight plans
- steps taken to avoid or minimize radiation exposure during a flight, *e.g.*, changes in the flight plan such as reduction of time spent outside the spacecraft or moving to a shielded portion of the spacecraft during increased solar activity

- raw data on the radiation environment and spacecraft characteristics and orientation, which were collected at the time of the astronaut's exposure to the radiation
- information on radiation detectors and measurement equipment including type, serial number, and calibration data
- biodosimetry data and computations that utilize these data
- computations of radiation doses, including method used to account for radiation quality and the tissue weighting factor (w_T)
- reports of monthly, annual and career radiation doses from space flights for each astronaut
- radiation dose estimates for biomedical activities that are associated with specific flights or research protocols
- radiation dose estimates from associated noncommercial aviation activities undertaken as part of mission requirements

9.1.1 *Records of Career Doses*

Dosimetry records constitute the formal documentation for each astronaut's space-related radiation exposure history and should contain the cumulative dose from space flight, mission-related aviation activities, and mission-related biomedical research. Since the radiation doses for each astronaut may not be assigned until well after completion of a flight (or may be revised as new information becomes available), NCRP recommends that the dosimetry records be updated as soon as possible after the radiation doses are assigned (or changed). The new doses should be communicated to the astronauts.

The dosimetry records should contain, or be linked to, all the basic information that is necessary to obtain the required dose-limit quantities (G_T and E). In addition to the astronaut's measured radiation doses (*e.g.*, from personal dosimeters or area monitors) for each point in time or monitoring period, the dosimetry records should contain the assigned value of D_T for each tissue or organ and the method by which $\overline{H}_T$ for each organ or tissue was obtained for use in the computation of E for that astronaut. The computed value of E should be linked to the standard operating procedure that describes the computation. The value of G_T for skin, lens of the eye, and bone marrow should be based on surface measurements, which are adjusted as described in Section 5. The dosimetry records should also be linked to information on radiation exposure conditions at the location and time of exposure.

Normally, astronauts are not exposed to radioactive materials that may be ingested, inhaled or absorbed through the skin. Participation in biomedical research studies that use radionuclides as tracers

would be an exception to this. When astronauts are monitored for internal radiation sources, the dosimetry records should contain the basic physical measurements (*e.g.*, activity) used to determine D_T to organs and tissues. Information on mode of intake and, where applicable, data on particle size distribution, chemical form, and chelation or decorporation therapy, as well as, procedures, bioassay data, biokinetic and dosimetric models, and other parameters used to determine D_T should be linked to the dosimetry records. For internally deposited radionuclides from these biomedical studies, H_T should be obtained using NCRP (1993) radiation weighting factors (w_R) and then used to compute E.

If an astronaut received occupational exposure from previous employment or military service, information on the identity of each former employer and the radiation exposure for each period of employment should be obtained. This information may be included directly in each astronaut's dosimetry records or may be kept in other files that are linked to the astronaut's dosimetry records.

Annually, each astronaut should receive a confidential report of his or her radiation dose assessment and information on the significance of the doses. The report should include career radiation doses in terms of E for stochastic effects and monthly and annual doses in terms of G_T for deterministic effects to skin, lens of the eye, and bone marrow.

In addition to occupational radiation dose, the report may contain information on radiation doses from diagnostic or therapeutic medical procedures. Astronauts should be provided with information that describes the significance of these nonoccupational doses and the potential biological effects.

9.1.2 *Records of Prospective and Retrospective Studies*

The probability that particular records will need to be retrieved depends on the purpose for which the records are to be used. The four major potential uses of archived dosimetry records are:

- evaluation of the radiation safety program
- compliance with the dose limits
- use in epidemiological research
- use in litigation

If dosimetry records for short term or career doses are updated (revised) in a timely fashion whenever relevant new information (*e.g.*, new values for w_T) becomes available, they will have greater value for prospective use in planning astronaut activities and in

retrospective studies. Linkages to other information as described above (Section 9.1) will facilitate broader analysis of calculations, computations, flight control plans, and other variables that may have affected the recorded doses.

9.2 Continuity of Records Over Time

Dosimetry records should provide continuity of career radiation doses from past, present and future missions. Continuity is important to evaluate trends in radiation doses among astronauts over time, for prospective estimation of doses, and for assessment of cumulative career doses. As discussed in Section 6.3.3, NCRP recommends that the dosimetry records include the low- and high-LET components of the radiation field. If possible, the dosimetry records for the high-LET component should be divided into its neutron plus high-energy secondary particle (from protons) component and its HZE-particle component.

9.2.1 *Existing Records and Unanalyzed Data Files*

As a general recommendation, NCRP advises that any existing data related to space missions be examined and compared to dosimetry records to confirm that radiation dose estimates are based on all available data. If previously unanalyzed data are found, NCRP recommends that they be analyzed and that a determination be made of the value of the data in estimating astronaut doses.

The amount of data that may exist, which could change the current career dose estimate for astronauts, may be considerable. Analysis of all these data may or may not have a significant effect on the recorded annual dose estimate. Therefore, NCRP recommends that the data be identified and that representative samples of the data be fully analyzed to determine the extent of their effect on current dose estimates.

9.2.2 *Future Adjustment of Records*

Dosimetry records should be updated retrospectively whenever there is a systematic change in methodology (*e.g.*, method of accounting for radiation qualities or w_T) or new information becomes available (*e.g.*, previously unanalyzed data). Any data that could affect the estimation of astronaut doses should be analyzed as soon as

possible or retrospectively to provide the best estimate. NCRP recommends that astronaut dose estimates be adjusted whenever differences in revised dose assessments exceed 30 percent of the original dose assessment (see discussion of accuracy in Sections 6.4.1 and 6.4.2).

9.3 Retention of Records

Determination of the retention period depends on the consequences of having or not having the information available when it is needed. Regulations specify minimum retention periods for the first two potential uses given in Section 9.1.2, generally within a time frame of years or possibly the lifetime of the individual. Consequences associated with potential future need for records for epidemiological research and litigation are difficult to predict. Need of records for these purposes may not arise for decades. NCRP (1992) recommends that records be maintained for specific periods of time appropriate for their intended purposes. Because of the unique features of astronaut radiation exposures, NCRP recommends at this time that records be maintained indefinitely.

Appendix A

Time-Dependent Variations in the Space Radiation Environment and the Need for Active Real-Time Monitoring

A.1 Background

Temporal changes in the external radiation environment occur by two major processes and one minor process:

- precession of the orbit within Earth's asymmetric magnetic field
- modulation of the sources by solar activity (both short- and long-term variations)
- change in altitude due to atmospheric drag and re-boost

In addition, there are local spatial variations within the Space Shuttle, ISS, or space suit due to the relative differences in shielding at locations visited by the astronaut. This requires an accurate knowledge of the time spent by the astronaut within the spatially distributed fields and the temporal field changes during those visits.

There are uncertainties in the external radiation environment. The properties of GCR are well known and the transmission through the geomagnetic field is adequately understood except during brief periods of large geomagnetic storms. Such storms result in little uncertainty in the accumulated fluence over a Space Shuttle or ISS mission. The neutron albedo is directly correlated to the GCR intensity and has been well characterized by satellite and balloon measurements and theoretical models. The LEO trapped proton environment is relatively stable with mainly long-term variations over the solar cycle but this time variation is poorly represented in current environmental

models and is a major source of uncertainty in Space Shuttle or ISS exposures. In addition, the trapped radiations are highly anisotropic; this anisotropy is not part of the usual environmental models.

SPEs cause short-term enhancements in the extraterrestrial radiation environment, the effects of which are mainly limited to the geomagnetic polar regions. Due to orbit precession, the worst-case SPE exposure occurs when the line of nodes (*i.e.*, the intersection of the equatorial plane with the orbital plane) is near 210 degrees longitude. Only the two prior and two succeeding orbits are important to exposure if the 210 degree line of nodes is coincident with the peak of the SPE intensity. The time of particle arrival relative to orbital precession is critical to exposure evaluation. A large geomagnetic storm could greatly enhance the radiation exposure if the peak storm is at the SPE peak intensity while the orbit plane is aligned in the worst-case orbit. The expected exposures from an SPE and their associated uncertainties depend on many variables. The above considerations apply to both Space Shuttle and ISS and during EVA. In addition to these sources, the trapped electrons are important for EVA. They are filtered from the interior of the Space Shuttle or ISS radiation environment by the micrometeoroid/debris bumper and pressure vessel and the resulting bremsstrahlung is unimportant compared to other LEO sources. The trapped electrons are highly variable with relativistic electron precipitation events occurring every few to several weeks. During these events, the fluence can rise suddenly by up to four orders of magnitude with slow decline over several days. These events are most important to skin exposures during EVA. The helmet provides significant protection to the lens of the eye especially with the visor in the down position.

Active detectors provide information, in real-time, on radiation fields inside and outside the spacecraft. This information is used for direct determination of D and H. Active dosimeters can be either area monitors or personal dosimeters. Active instruments can also measure particle fluence and fluence rates as a function of particle charge and energy. Active devices, by virtue of their immediate availability, are valuable sources of data needed for timely implementation of immediate dose management and routine ALARA.

The instrumentation should be capable of providing dose rate as well as integrated doses with time resolution from several minutes to several days.

Information should, where possible, be immediately available to astronauts in space as well as through downlink to the ground where more extensive analysis can be performed.

Active dosimeters should be used inside and outside of the spacecraft. Some serve as area monitors at fixed locations while others are portable area monitors that can be moved to various locations, or even carried on the astronaut's person, including during EVA.

A.2 Types of Active Detectors Used in Space

A.2.1 *Tissue Equivalent Proportional Counters*

A TEPC is a gas filled detector that is operated in the proportional mode such that the signal generated is proportional to the initial ionization generated in the gas (Rossi and Rosenweig, 1955). The tissue equivalence of a TEPC is based on the composition of the wall that defines the gas cavity as well as the composition of the gas itself. Generally the wall is fabricated from a conducting plastic such as A-150® (Standard Imaging Inc., Middleton, Wisconsin). Since a low-density gas is used to simulate very small volumes of material, the Bragg-Gray cavity theory would apply for any gas mixture. However, in order to avoid variations in stopping power ratios (S_{wall}/S_{gas}) for the vast array of incident particles, the gas is also chosen to have an atomic composition of soft tissue as well as retain the properties necessary for gas multiplication in a high electric field. It is usually a combination of carbon dioxide, argon, and either methane or propane.

Another feature of a TEPC is that the quantity of gas in the cavity is carefully regulated. The reason for this is that energy deposition from the passage of a charged particle in the gas can simulate energy deposition by that particle in a volume of tissue having dimensions similar to a mammalian cell. Thus, energy deposition events measured by TEPC should reflect the pattern of energy deposition in microscopic volumes. This in turn provides information on the quality of the incident radiations.

The basis for simulating small volumes of tissue rests in the fact that cross sections for ionization at the atomic and molecular level are independent of density. For example, energy transfer is conserved providing that:

$$\rho_t \, x_t = \rho_g \, x_g, \tag{A.1}$$

where:

x_t = the thickness of tissue to be simulated
ρ_t = the density of tissue, taken to be 1 g cm^{-3}
x_g = the thickness of the gas cavity in the detector
ρ_g = the density of the gas in the detector

A common case is when a spherical or cylindrical detector with a diameter of 10 mm is used to simulate a volume of tissue with a diameter of 1 μm. For this situation, the gas pressure in the cavity would be about 6,700 Pa. These conditions can be achieved routinely and provide signals that are reasonably easy to process and record. They have been successfully used for dosimetry in mixed fields consisting of fast neutrons and photons, as well as for manned space missions.

For heavy charged particles passing through a very small amount of material, the energy lost is small and LET remains unchanged. If all of the energy transferred to the volume of material is absorbed within the volume then:

$$\varepsilon = L\,x \tag{A.2}$$

where:

ε = the energy deposited (keV)
L = LET (keV μm^{-1})
x = the path length through the material (μm)

Thus, energy deposition in a cell for this case depends on both LET and path length or trajectory through the volume. This should also be the case for a TEPC.

Microdosimetry was developed to accommodate these principles (ICRU, 1983). It is known that there is an association between RBE and LET. This has been extended to radiation protection where Q is also a function of LET. Thus, the energy deposition in a cell should be divided by a length if it is to be related to LET. However, the length through the cell may not be known and this changes from event to event. Thus, a quantity called lineal energy (y) was defined such that:

$$y = \frac{\varepsilon}{\bar{\ell}}\,, \tag{A.3}$$

where:

y = the lineal energy for an event (keV μm^{-1})
ε = the energy deposition associated with the event (keV)
$\bar{\ell}$ = the mean chord length for the distribution of possible trajectories through the simulated volume of tissue (μm)

Thus, y is a random variable that depends on the distribution of energy deposition events in the volume of interest and a constant that depends on the geometry of the tissue. The mean chord length was chosen for the denominator of y because for a distribution of random events with constant LET, the mean value of y will be numerically equivalent to LET.

For the case where LET of the particles is constant, the response of a TEPC will reflect the chord length distribution for the simulated volume of interest. Figure A.1 shows the expected distribution of $f(y)$ for a uniform isotropic particle fluence [$\Phi(L)$] having a single value of L equal to 215 keV μm^{-1}. Curve 1 represents a sphere with a diameter of 1 μm and Curve 2 represents a cylinder with diameter and length equal to 1 μm. Although the mean chord length happens to be the same for both of these distributions, the pattern of energy deposition events is distinctly different.

It is clear that even for an idealized case, the measured distribution $f(y)$ will not be a direct representation of the distribution of LET for the incident $\Phi(L)$. The distribution of $f(y)$ is a convolution of $\Phi(L)$ and $f(x)$, the distribution of path lengths (x). Thus, if $f(x)$ is known, it should be possible to deconvolute $f(y)$ and obtain $\Phi(L)$. When $f(x)$ is the triangular distribution for a sphere, the deconvolution reduces to an analytical expression that is easy to solve. Other distributions of $f(x)$, including that for a cylinder, usually require complicated numerical procedures.

The situation for heavy nuclei is more complicated. The energy deposition does not occur in a limited region surrounding the track. High-energy delta rays remove energy away from the axis of the track. Some of the energy can actually escape from the volume of interest. For the same reason, there can be energy deposition in a volume of material that was not traversed by a track at all. In addition to these factors, there is additional variance in the measured signals due to energy straggling, gas multiplication, and effects due to the fact that the density of the wall surrounding the cavity is 40,000 times greater than the density of the gas.

Curve 3 in the following Figure A.1 is the distribution $f(y)$ measured in a spherical TEPC exposed to ^{56}Fe particles at 400 MeV n^{-1} (L = 215 keV μm^{-1}) (Gersey *et al.*, 2002). It clearly is not a simple triangle. There is a broad peak in the distribution that resembles a triangle. These events are from particles that pass through the gas cavity, but the energy absorbed in the cavity is less than L times x because some high-energy delta rays escape the sensitive volume. There is also a pronounced peak of events with very small values of energy deposition. These events correspond to particles that do not pass through the gas cavity but intersect the plastic wall surrounding

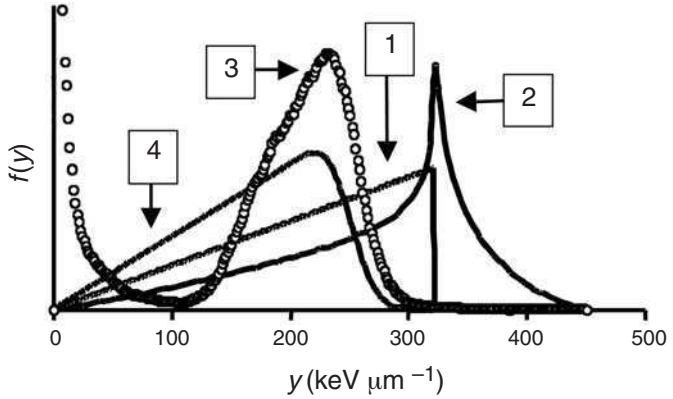


Fig. A.1. Distributions of y in a TEPC for a uniform fluence of ^{56}Fe at 400 MeV n^{-1}. Curves 1 and 2 represent the case where energy deposited is equal to L times the chord length in a sphere (Curve 1) and a cylinder (Curve 2). Curve 3 is data from measurements with a spherical detector. Curve 4 is the result from a calculation using restricted LET (L_Δ) and straggling.

the cavity. Some of the delta rays originating in the plastic manage to enter the cavity and deposit energy. There is also a tail of events that corresponds to very large energy depositions. These events are caused by particles that just graze the inside wall of the detector. This produces a flood of low-energy delta rays that combine to generate a very large energy deposition event in the gas (Rademacher *et al.*, 1998). These patterns have been observed for ^{56}Fe from 200 to 1,000 MeV n^{-1} as well as for other ions such as ^{28}Si, ^{16}O, and ^{12}C. The magnitude of these effects will change with the charge and velocity of the heavy ion making the deconvolution process even more complicated when L has a large range of values.

A model has been developed to compute energy deposition by HZE particles in order to predict the measured distribution of $f(y)$ by a TEPC exposed to space radiation (Shinn *et al.*, 1999; Xapsos, 1992). This computation takes into account chord-length distributions through the detector similar to Curves 1 and 2 in Figure A.1. Energy deposition is obtained using a model for restricted LET (L_Δ) to simulate delta-ray escape and a lognormal distribution of energy lost along the track to simulate particle straggling. The results of this model for a 1 μm diameter sphere are shown as Curve 4 in Figure A.1. When compared with the expected triangle for a sphere, there is a decrease in energy deposition as well as a smoothing effect due to straggling. The model does not however reproduce the data

corresponding to very low and very high-energy depositions generated in the wall of a TEPC.

Although TEPC does not provide a direct measurement of LET distribution of the incident particles, it does provide valuable information relating to the quality of the radiation, and therefore allows an estimate of H to a small mass of tissue at the location of TEPC. One important issue is related to the integrated spectrum of energy deposition in terms of D. Energy that is lost by the escape of delta rays when the particles pass through the sensitive volume must be replaced by delta rays that originate outside of the volume (*i.e.*, from the wall). Table A.1 shows results for the fraction of D obtained for a uniform fluence of ^{56}Fe particles at 400 MeV n^{-1} from the data shown in Figure A.1. Also shown are results for the first and second moments of the lineal energy.

The measured data for ^{56}Fe at 400 MeV n^{-1} indicate that TEPC does satisfy charged-particle equilibrium and therefore gives a correct estimate of D to tissue for this HZE particle. However the restricted stopping power model underestimates the dose by about 20 percent because it does not consider energy transfer from particles that pass near but not through the sensitive volume of the detector. Additional experiments and data will be required to determine the extent to which charged-particle equilibrium is achieved for HZE particles other than ^{56}Fe.

As expected, the frequency-averaged lineal energy ($\bar{y}_f$) is numerically equivalent to LET for the idealized distributions with a sphere and cylinder. However this relationship is not preserved for the ^{56}Fe data or L_Δ model. This is further confirmation that $f(y)$ is not a surrogate for $\Phi(L)$. It is however interesting that the dose-averaged lineal energy ($\bar{y}_D$) is also different for all four distributions but the value from the ^{56}Fe data is numerically equivalent to LET. This has been demonstrated for ^{56}Fe from 200 to 1,000 MeV n^{-1} (Gersey *et al.*,

TABLE A.1—*Estimates of the fraction of D, $\bar{y}_f$ and $\bar{y}_D$ associated with the curves shown in Figure A.1.*

	D (%)	$\bar{y}_f$ (keV μm^{-1})	$\bar{y}_D$ (keV μm^{-1})
LET in sphere[a]	100	215	241
LET in cylinder[a]	100	215	270
Fe-56 data	104	146	216
L_Δ model	81	174	193

[a]Refers to the ideal case where energy deposited is equal to LET times chord length.

2002). Thus, it is possible that even though the measured spectrum from a TEPC is not a direct determination of LET, $\bar{y}_D$ is coupled to LET in a way that is useful for radiation protection purposes.

A TEPC is also sensitive to high-energy neutrons (Badhwar *et al.*, 2000; in press). Charged particles generated in the walls of a TEPC will deposit energy in the gas cavity. The pattern of energy deposition is similar to charged particles originating outside of the detector. Thus, a TEPC automatically includes the contribution from neutrons that either interact in the detector or elsewhere in the spacecraft. A TEPC could be placed within a hydrogenous phantom to create the charged-particle intensity that would be expected from neutron interactions in a person.

TEPC systems currently used by NASA resolve energy deposition events in the range from a fraction of a kiloelectron volt ($y \sim 0.3\,\text{keV}\,\mu\text{m}^{-1}$) to 800 keV ($y = 1{,}000\,\text{keV}\,\mu\text{m}^{-1}$). The lower bound is determined by electronic noise. The upper bound by saturation of shaping amplifiers. As electronic components improve, it should be possible to reduce noise and extend the range of these detectors.

A.2.2 *Semiconductor Detectors*

Detectors based on thin semiconductor crystals measure the ionization energy loss of an incident particle. Energy deposited within the detector can be collected and analyzed in real-time, and data from one or more such detectors can be convoluted to determine a particle's charge and total energy. The average energy necessary to create an electron hole pair (ion pair) is approximately 10 times lower in a silicon diode compared with gas. This results in improved energy resolution and thus provides an opportunity for precise estimates of LET for the incident particles.

The detectors are planar with a thickness ranging from 50 to 5,000 μm and diameters ranging from 10 to 60 mm. High-energy charged particles pass through the sensitive volume. The magnitude of the signal (dE) registered by the detector is related to the trajectory (angle of incidence) and LET of the incident particle. Energy resolution improves as dE increases. If the acceptance is restricted to small angles, the path through the detector is approximately equal to the thickness (x_d) and $L \sim \text{dE}/x_\text{d}$. Under this approximation, a detector can yield D, Q and H for charged particles. If the variation in path length is restricted to 10 percent, the incidence angle must be limited to 26 degrees, which corresponds to a solid angle acceptance of 0.1. This means that approximately 90 percent of the incident particles must be rejected.

Some of these restrictions can be eliminated by adding one or more position sensitive solid-state detectors (PSD) to the system. For example, resistive charge division is used to determine the location of the incident particle in the plane of the detector. Data from two or more PSDs placed a fixed distance apart can be used to reconstruct the trajectory (incident angle) of the particle and thus the true path length (dx) through the dE detector. The dE/dx thus obtained is L_∞. There must be sufficient separation between the PSDs in order to measure the incident angle. Limits on the sensitive area, and separation between PSDs have the effect of restricting the angular acceptance of this system.

For dosimetry purposes alone, a thick detector ($x_d \geq 500$ μm) with an area of about 300 mm^2 (diameter ~20 mm) should be sufficient for a first approximation to D and Q, and devices of this type that are sufficiently compact to be worn on an astronaut's person exist. For this case the interpretation of the pulse height spectrum in terms of H must take into consideration that some of the particles were incident directly upon the dosimeter and some went through the astronaut's body. In addition, this system cannot distinguish slow particles that stop in the detector from those that penetrate. Thus, dE may be correct for estimating D, but setting $dx = x_d$ may underestimate L.

Detector systems that contain several solid-state detectors can eliminate some of the problems mentioned above (Badhwar *et al.*, 1995b; Doke *et al.*, 2001). These arrangements are often called particle telescopes since they view a selected region of space. PSDs can be used to define the trajectory. The distribution of energy loss in successive detectors is a unique signature of a particle's charge and energy, and instruments of this type have been flown on satellites; however, the number of detectors required may render this method impractical for dosimetry. Combining a thin detector with one sufficiently thick to stop a charged particle is effective for charge identification, but also may be impractical for many of the highly energetic particles found in space.

There have been attempts to make omnidirectional detector arrays, in contrast to the collinear pattern used in particle telescopes. One design is based on making a cube from silicon strip detectors (Yoshihira *et al.*, 2000). The detector would measure dE and position of the incident particle as it entered and exited the cube. The position information is used to compute the trajectory of the particle and dx in each detector. This could then provide $\Phi(L)/d\boldsymbol{\Omega}$ as a function of direction or $\Phi(L)$ integrated over all directions.

A single active silicon detector system has been made compact enough to serve as a personal dosimeter (Badhwar, 2000). It provides

on-demand readout of accumulated D as well as $\dot{D}$. Power is obtained from a stack of lithium batteries that last for about 28 d. It can be modified to operate from space suit power during an EVA.

A.2.3 *Cerenkov Counters*

An alternative approach is to make a determination of dE/dx and velocity (β). One way to do this is by measuring Cerenkov radiation. The procedure is based on using thin solid-state detectors to measure dE/dx and a Cerenkov counter to measure the photon emission (dN/dx) in a gas or liquid. These are related to the incident particle in the following manner:

$$\mathrm{dE/d}x \propto \frac{\mathrm{Z}^2}{\beta^2}\,, \tag{A.4}$$

$$\mathrm{dN/d}x \propto \mathrm{Z}^2 \left(1 - \frac{1}{\beta^2 n^2}\right), \tag{A.5}$$

where n is the refractive index of the medium in the Cerenkov counter. The two equations can be solved simultaneously to obtain the charge of the incident particle (Z) and velocity (β).

The Cerenkov counters used in these applications generally have a threshold of about $\beta = 0.5$ (200 MeV n^{-1}) and saturate at about $\beta = 0.75$ (500 MeV n^{-1}).

A.2.4 *Ionization Chambers*

Ionization chambers can be used to measure D. They, however, do not give information on the quality of the incident radiation for mixed radiation fields. There is also a problem of recombination along the track of high-LET particles.

However, ionization chambers can be used as screening detectors for solar events or to monitor enhanced electron intensity following magnetic storms. They could be employed as area monitors inside and outside of the spacecraft in order to confirm that dose rates do not approach or exceed specified values.

Ionization chambers have been designed to obtain the quality factor in mixed radiation fields based on columnar recombination of high-LET radiation (Zielczynski, 1962). Measurements are made over a range of voltages from 2 to 1,200 V. The data are used to determine the change (slope) of the measured current as a function of voltage. This slope is related to the quality factor through an empirical formula (Baarli and Sullivan, 1965). Recombination

chambers have been used to obtain the quality factor for mixed fields at high-energy particle accelerators (Cossairt and Elwyn, 1987; Hofert and Raffnsoe, 1980). It is not known if the empirical relationships will remain the same for space radiations such as a trapped protons or GCR. It is also imperative that the dose rate remains constant while sweeping the voltage, which can take up to an hour at low dose rates. This may be impractical in LEO and therefore a second ion chamber with constant voltage would be necessary for normalization.

Appendix B

Computational Methods

The determination of the types and energy distributions of particles, transmitted through a shield material and through astronaut tissues, requires the solution to radiation transport equations of the process with appropriate boundary conditions for the external space radiation environment. The relevant transport equations are the linear Boltzmann equations derived on the basis of conservation principles (Wilson *et al.*, 1991) for the fluence $\Phi_i(x,\boldsymbol{\Omega},E)$ of particles of type i moving in direction $\boldsymbol{\Omega}$ with energy E as:

$$\boldsymbol{\Omega} \cdot \nabla \Phi_i(x,\boldsymbol{\Omega},E) = \sum \left[\int \sigma_{ik}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E') \, \Phi_k(x,\boldsymbol{\Omega}',E') \, d\boldsymbol{\Omega}' \, dE' \right] - \sigma_i(E) \, \Phi_i(x,\boldsymbol{\Omega},E), \tag{B.1}$$

where $\sigma_i(E)$ is the rate of removal of particles of type i with energy E moving in direction $\boldsymbol{\Omega}$, $\sigma_{ik}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E')$ are the media macroscopic cross sections for various atomic and nuclear processes k producing particles of type i with energy E moving in direction $\boldsymbol{\Omega}$, including spontaneous disintegration. In general, there are hundreds of fluence terms $[\Phi_i(x,\boldsymbol{\Omega},E)]$ with several thousand cross-coupling terms $[\sigma_{ik}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E')]$ through the integral operator in Equation B.1. The total cross section $[\sigma_i(E)]$ with the medium for each particle type of energy E may be expanded as:

$$\sigma_i(E) = \sigma_{i,at}(E) + \sigma_{i,el}(E) + \sigma_{i,r}(E), \tag{B.2}$$

where the first term refers to collision with atomic electrons (at), the second term is for elastic nuclear scattering (el), and the third term describes nuclear reactive processes (r). The microscopic cross sections and average energy transfer are ordered as follows:

$$\sigma_{i,at}(E) \sim 10^{-16} \text{ cm}^2 \text{ for which } \Delta E_{at} \sim 10^2 \text{ eV}; \tag{B.3}$$

$$\sigma_{i,el}(E) \sim 10^{-19} \text{ cm}^2 \text{ for which } \Delta E_{el} \sim 10^6 \text{ eV; and} \tag{B.4}$$

$$\sigma_{i,r}(E) \sim 10^{-24} \text{ cm}^2 \text{ for which } \Delta E_r \sim 10^8 \text{ eV}. \tag{B.5}$$

This ordering allows flexibility in expanding solutions to the Boltzmann equation as a sequence of physical perturbative approximations. It is clear that many atomic collisions ($\sim 10^6$) occur in a centimeter of ordinary matter but transferring little energy per collision, whereas $\sim 10^3$ nuclear coulomb elastic collisions occur per centimeter but with significant energy transfer. In distinction, nuclear reactions are separated by a fraction to many centimeters depending on energy and particle type but with large energy transfers. Atomic interactions are treated with an energy moments expansion in which the first term is related to LET and higher order moments are related to range straggling. The secondary electrons form the energy deposit around the ion path. The elastic scattering is treated as lateral diffusion. Special problems arise in the perturbation approach for neutrons for which $\sigma_{i,at}(E) \sim 0$, and the nuclear elastic process appears as the first-order perturbation. The neutron-coupling problem has been the recent focus of research (Clowdsley *et al.*, 2000) and further described below along with the reactive processes.

The double differential particle production and fragmentation cross sections $[\sigma_{ik}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E')]$ of Equation B.1 are separated into an isotropic contribution and a remainder as:

$$\sigma = \sigma_F + \sigma_{iso}, \tag{B.6}$$

where the remainder σ_F consists of only forward directed secondary particles and σ_{iso} is dominated by lower energy particles produced in the reaction. The low-energy charged particles are of short range due to atomic interaction processes and may be solved analytically (Wilson *et al.*, 1991) but the low-energy neutrons have no atomic interactions and require a different solution technique (Clowdsley *et al.*, 2000). The solution to Equation B.1 can likewise be separated into two parts for which σ_F appears only in Equation B.1 with solution Φ_F and a second equation in which σ_{iso} appears in Equation B.1 but with source terms from coupling to the Φ_F field through σ_{iso}. The solution to Equation B.1 for Φ_F can be written in operational form as:

$$\Phi_F = G_F \Phi_B, \tag{B.7}$$

where Φ_B is the inbound field at the boundary, and G_F is the Green's function associated with σ_F, which reduces to a unit operator on the boundary denoted by Γ. Standard practice in space radiation protection replaces Γ as required at some point on the boundary and along a given ray by the corresponding Γ_N evaluated for normal incidence (N) on a semi-infinite slab (Wilson *et al.*, 1994). The errors in this approximation are made only for the Φ_F field and are second order in the ratio of beam divergence and radius of curvature of the object, rarely exceed a few percent for space radiations, and are

always conservative (Wilson *et al.*, 1994). The replacement of Γ by Γ_N as a highly accurate approximation for space applications has the added advantages that Γ_N is the natural quantity for comparison with laboratory experiments and has the following property: if Γ_N is known at a plane a distance x_o from the boundary (assumed at the origin), then the value of Γ_N at any plane $x \geq x_o$ is:

$$G_N(x) = G_N(x - x_o)\, G_N(x_o). \tag{B.8}$$

Setting $x = x_o + h$, where h is small and of fixed step size gives rise to highly efficient marching procedure of the radiation transport code HZETRN (Wilson *et al.*, 1997). Allowing x and x_o to take arbitrary values gives rise to the nonpertabative solution methods. There remains the evaluation of the remainder terms σ_{iso} of Equation B.1, especially the low-energy neutron transport.

The remainder of Equation B.1 following the separation given by Equation B.6 is:

$$\boldsymbol{\Omega} \cdot \nabla \Phi_i(x,\boldsymbol{\Omega},E) = \sum \Big[\int \sigma_{iso,ik}(E,E')\, \Phi_k(x,\boldsymbol{\Omega}',E')\, d\boldsymbol{\Omega}'\, dE' \Big] - \sigma_i(E)\Phi_i(x,\boldsymbol{\Omega},E) + g_i(E,x), \tag{B.9}$$

where the source term $[g_i(E,x)]$ results from the collisional σ_{iso} source with the Φ_F field. As mentioned above, the charged particle fields of Equation B.9 can be solved analytically leaving the low-energy neutrons fields to be evaluated. Energy multigroup methods are currently used for evaluation of Equation B.9 for the neutron fields (Clowdsley *et al.*, 2000). The solution for the diffuse component depends on the surrounding material and the accumulation of the neutrons produced in and scattered from the massive material of human occupied spacecraft is an essential part of solution of the Boltzmann equation. The diffuse charged particle component is simpler since the atomic interactions tend to dominate in the appropriate energy range.

The extent of the nuclear interaction cross section database required for the transport of cosmic rays spans most nuclear-reaction physics from thermal energies to energies above tens of GeV n^{-1}, including a large number of projectile and target material combinations. The types of cross sections required for the transport involve total yields and secondary energy spectra for one-dimensional transport and double differential cross sections in angle and energy for three-dimensional transport. Fortunately, neutron and proton cross sections have been studied at some length in the past. Nuclear-reaction modeling is required, especially for light and heavy ion projectiles, to understand the basic physical processes, and to extrapolate the limited, available experimental data between projectile

energies and projectile-target combinations. The usual approach to database generation is the use of Monte Carlo models or hydrodynamic models with limited usefulness and success. The best approach has been to develop solution procedures of the basic quantum mechanics (Cucinotta *et al.*, 1993; Wilson, 1974).

A microscopic theory for the description of nuclear fragmentation is being developed through the study of the summation of the nucleus-nucleus, multiple-scattering series for inclusive reactions where a single reaction species is considered. This approach originated in a theory for high-energy alpha-particle fragmentation (Cucinotta *et al.*, 1993) and has been extended to recast the abrasion-ablation model in microscopic form (Cucinotta and Dubey, 1993). The microscopic theory represents a unified approach where a single formalism generates all the cross sections required for heavy-ion transport. The evaluation of the microscopic theory requires the interaction amplitudes among basic nuclear constituents. The strong interaction and quantum phase space limitations (Pauli principle) modify the amplitudes for bound constituents and have important impact on elastic and reactive processes (Tripathi *et al.*, 1999). Basic nuclear theory and media modified interaction amplitudes with the optical theorem can now, for the first time provide high quality total and reactive cross sections as recently incorporated into the Langley 90 database (Tripathi *et al.*, 1998; 1999) and have been adopted by other groups and agencies and stand ready for application to the HZE fragmentation process. A recent blind test in iron fragmentation experiments of various models has been very encouraging for future database generation (Cucinotta *et al.*, 1998; Zeitlin *et al.*, 1997).

Appendix C

Thermoluminescence Dosimetry Materials

The more usual TLD materials for passive personal radiation dosimetry have been reviewed and described by McKeever *et al.* (1995). For dosimetry in LEO, two materials have been used most often, namely, lithium fluoride, doped with magnesium and titanium (LiF:Mg,Ti) and calcium fluoride, doped with thulium (CaF_2:Tm).

C.1 Lithium Fluoride, Doped with Magnesium and Titanium

Radiation dosimetry-quality lithium fluoride generally comes in three forms. The differences between them lie in the isotopic abundance of lithium, thus: natural abundance (92.5 percent ^{7}Li and 7.5 percent ^{6}Li), enriched in ^{6}Li (95.5 percent), and enriched in ^{7}Li (99.5 percent). Such detectors are available from a variety of manufacturers. Perhaps the most widely known forms are known as TLD-100®, TLD-600® and TLD-700®, respectively, using the original trade names of the old Harshaw Chemical Company (now Saint-Gobain Industries). Each of these is doped with magnesium, titanium and hydroxyl impurities. Since ^{6}Li has a large cross section for neutron interaction, *via* the reaction ^{6}Li(n,α)^{3}H, then ^{6}Li-enriched versions (*e.g.*, TLD-600®) are more sensitive to thermal neutrons (below ~1 keV) than either of the other versions (such as TLD-100® or TLD-700®).

The usual procedure for using LiF TLDs is to anneal the sample at 400 °C for 1 h. This is then followed by either a slow cool to 80 °C, and a hold at this temperature for 24 h, or a slow cool to 100 °C, and a hold at this temperature for 2 h (although other similar recipes are often used) (Furetta and Weng, 1998; Horowitz, 1984b; McKeever,

1985; McKeever *et al.*, 1995; Niewiadomski, 1993). Reproducible control of the temperature and the timing of the heating and cooling cycles are considered to be critical. The purpose of the heating schemes is two-fold: (1) to reset the defect equilibrium state within the samples after each use, and (2) to empty charge from stable defects which may remain after the first irradiation and readout cycle. To ensure stable resetting of the defect equilibrium the lengthier, but more reliable, 400 °C for 1 h plus 80 °C for 24 h is often recommended (McKeever *et al.*, 1995).

A typical glow curve for LiF:Mg,Ti (in this case TLD-100®) treated by annealing at 400 °C for 1 h plus 100 °C for 2 h is shown in Figure C.1. Although these data were obtained with the faster 400 °C for 1 h plus 100 °C for 2 h anneal, they serve to demonstrate the complexity of the glow curve. The sample has been irradiated with 1.5 MeV protons (1.8×10^{10} protons cm^{-2}). The glow curve is a complex overlap of several individual signals. The figure shows two methods for deconvoluting the signal into its component parts. No single deconvolution model has yet been agreed upon for the glow curve from LiF:Mg,Ti but, nevertheless, the data of Figure C.1 show the complexity of the glow curve with its multiple components. Glow curves for other versions of LiF:Mg,Ti (*e.g.*, TLD-600® and TLD-700®) are similar.

The TL signal corresponding to Peak 5 (Figure C.1) is usually taken to be the signal of interest. The response of LiF:Mg,Ti to absorbed dose from gamma rays indicates a linear-supralinear behavior, with saturation occurring near 10^3 Gy (McKeever *et al.*, 1995). Supralinearity of the signal starts at a few gray (McKeever and Horowitz, 1990). The dose response of this material to all low-LET (*i.e.*, <10 keV μm^{-1}) radiation is essentially identical to that of ^{60}Co or ^{137}Cs irradiation. Likewise, the dose responses of other versions of LiF:Mg,Ti (*e.g.*, TLD-600® and TLD-700®) are generally considered to be similar to that of TLD-100®.

The response of the material to heavier charged particles, however, changes considerably from that resulting from irradiation with low-LET irradiation. The increased ionization density around the track of the incident particle results in a decrease in sensitivity and a decrease in supralinearity for Peak 5, but with a concomitant increase in sensitivity and supralinearity for the higher temperature peaks (*i.e.*, Peaks 6 to 10 in Figure C.1). The change in the shape of the LiF glow curve as a function of LET of the particle is represented in the data of Figures C.2 and C.3.

The normal approach for determining the absorbed dose from a radiation source (photon or particle) using LiF:Mg,Ti dosimeters is

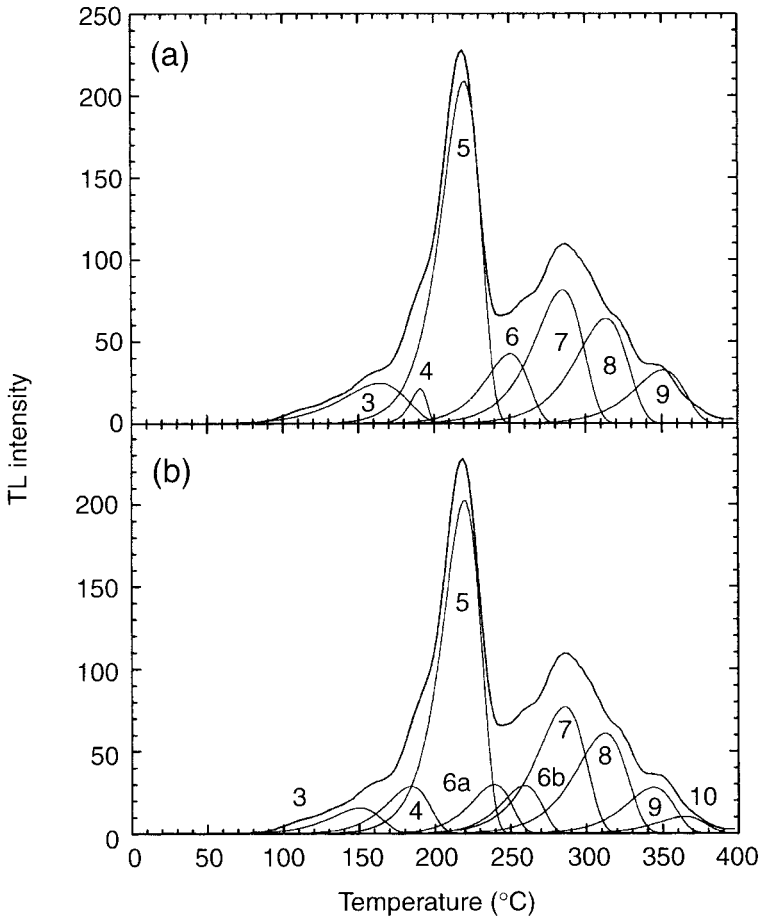


Fig. C.1. TLD-100® glow curve for 1.5 MeV protons (1.8×10^{10} protons cm^{-2}) following an anneal treatment of 400 °C for 1 h plus 100 °C for 2 h. The heating rate was 1 °C s^{-1} (Aviles *et al.*, 1999). The figure shows the results of two different methods [(a) and (b)] for deconvoluting the signal into its component parts.

to calibrate the Peak 5 signal against absorbed dose from gamma rays (*e.g.*, using ^{137}Cs or ^{60}Co).[11] Thus, one determines the gamma-ray dose from ^{137}Cs or ^{60}Co that is required to produce the same signal intensity as the incident radiation field (*i.e.*, one determines the

[11]For first-order TL processes (as in LiF) the peak area is proportional to peak height. The best accuracy these days is achieved with glow curve deconvolution in order to separate the individual responses of the individual peaks (Horowitz and Yossian, 1995). This is particularly important since there are multiple overlapping peaks in TLD materials, each of which has a slightly different response to the various charged particles expected in a space environment.

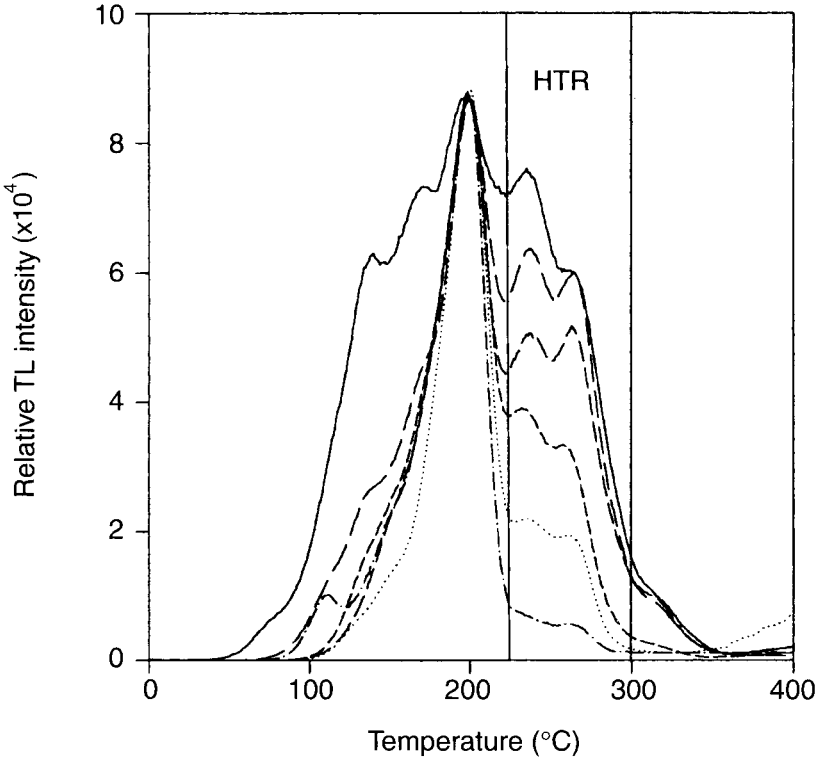


Fig. C.2. Change in the shape of the glow curve (from TLD-600®) as a function of charge particle type. "HTR" is the high temperature ratio and is the integrated area under the curve, between the limits shown, divided by the height of Peak 5. The data in this Figure have been normalized to the maximum of Peak 5 to facilitate calculation of HTR. The irradiations (from top to bottom) are: ^{241}Am alpha, 174 keV μm^{-1}; thermal neutrons, 130 keV μm^{-1}; ^{19}F ions, 102 keV μm^{-1}; ^{19}F ions, 30 keV μm^{-1}; ^{12}C ions, 12.8 keV μm^{-1}; and ^{60}Co gamma rays (Schoner *et al.*, 1999).

equivalent ^{137}Cs or ^{60}Co gamma-ray dose in gray). It was noted above that the sensitivity of Peak 5 decreases with increasing LET. For a single species of radiation, one thus needs to account for this dependence in order to determine the equivalent gamma-ray dose. In Figure C.4 we see the change in the efficiency of Peak 5 (for TLD-700®) as a function of LET. In this case, the normalization dose is obtained from ^{60}Co. To be noted is an over-response caused by high-energy protons with respect to the gamma-ray dose, and a monotonic decrease in sensitivity for LET greater than approximately 10 keV μm^{-1}.

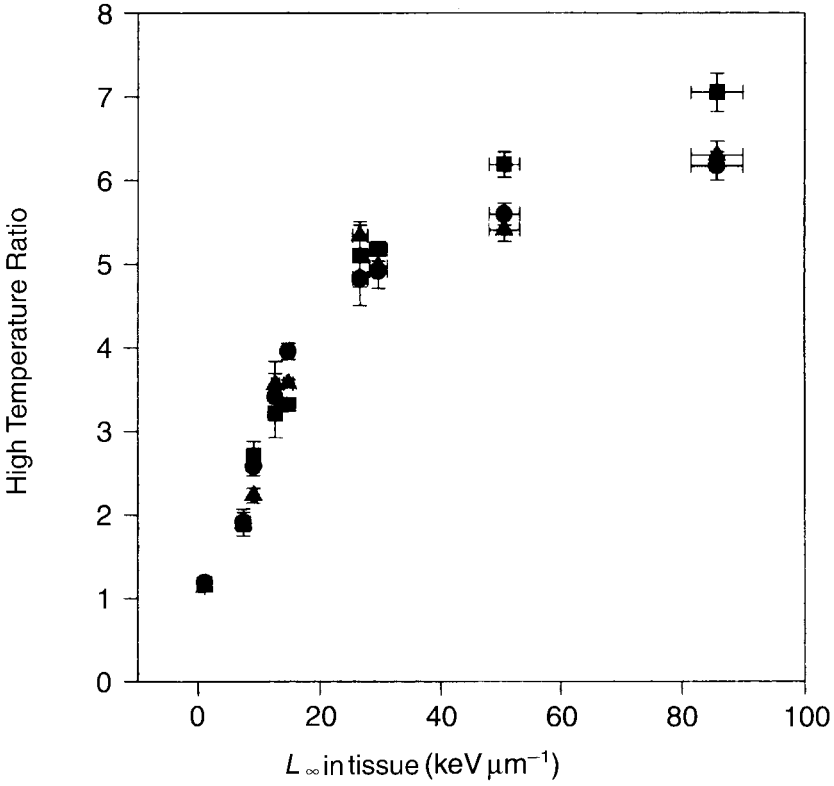


Fig. C.3. High temperature ratio (HTR) plotted against LET (L_∞) for TLD-100® (●), TLD-600® (■), and TLD-700® (◆) (Schoner *et al.*, 1999).

Similar data have been published elsewhere (*e.g.*, Horowitz, 1984b; McKeever, 1985; Yasuda and Fujitaka, 2000). The proton over-response indicated in Figure C.4 is ~10 percent, which is about the same as that reported elsewhere (Horowitz, 1984b; Yasuda and Fujitaka, 2000). However, larger over-responses have been reported [*e.g.*, Schoner *et al.* (1999) report a proton over-response of ~20 percent].

Benton *et al.* (2000) define the efficiency function $\varepsilon(L)$ in three regions of LET, thus:

$$\varepsilon(L) = 1, \tag{C.1a}$$

for $L < 2$ keV μm^{-1};

$$\varepsilon(L) = a_1 + b_1(\log L) + c_1(\log L)^2, \tag{C.1b}$$

for $2 \leq L \leq 50$ keV μm^{-1}; and

$$\varepsilon(L) = a_2 + b_2(\log L) + c_2(\log L)^2, \tag{C.1c}$$

for $L > 50$ keV μm^{-1};

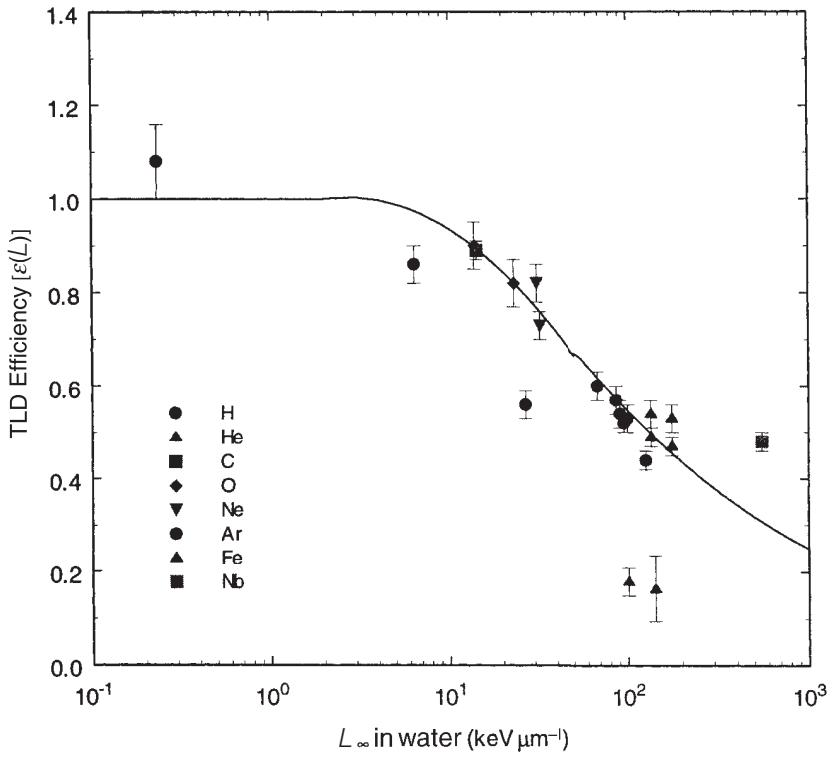


Fig. C.4. Response of Peak 5 from TLD-600® and TLD-700® to dose-averaged LET (Equation C.1). The response is normalized to ^{60}Co gamma rays, and is therefore defined as the TL efficiency [$\varepsilon(L)$] with respect to ^{60}Co (adapted from Benton *et al.*, 2000).

where $a_1 = 0.9650$, $b_1 = 0.1805$, $c_1 = 0.2100$, $a_2 = 1.7536$, $b_2 = 0.8060$, and $c_2 = 0.1016$. This ignores the proton overresponse at low-LET. From the available published data the conclusion is reached that this material does indeed overrespond to high-energy protons. However, some of the data are equivocal, and the extent of the overresponse is not clear, differing by several percent from report to report. Important issues include the precise batch of LiF used, the exact annealing conditions used (temperatures, duration, cooling rates, etc.) and the region of interest used in the determination of the TLD response (*i.e.*, integration between temperature X and Y, peak height calculation, etc.) and, of course, the reliability of the dosimetry in the individual reports.

Since the detailed TLD response is a function of the pattern of energy deposition around the particle track (*i.e.*, the track structure),

the precise behavior will be dependent upon both particle energy (E) and particle charge (Z). In particular, the radius of the track increases as Z increases and thus two particles having the same E but different Z are not expected to produce the same value of $\varepsilon(L)$. Data by Avila *et al.* (1999) and Geiss *et al.* (1998) on the efficiency of TL from LiF:Mg,Ti for several particles as a function of both E and Z illustrate the difficulty of providing a simple correction for the E,Z-dependence. An effective means to deal with this through calibration of TLDs for each particle type is not trivial since the number of different types of charged particle in the space radiation field is too large. However, an algorithm to calculate the efficiency (ε) as functions of both E and Z is described by Geiss *et al.* (1998) and this may prove to be a promising approach.

For space flight, particles of $Z > 26$ are of less importance (Benton *et al.*, 2000). Also to be noted is a reported "non-universality" of $\varepsilon(L)$ for a given material (Horowitz, 1984b). Variations in the defect structure (impurity content, defect equilibrium, etc.) lead to variations in the exact shape of the $\varepsilon(L)$ curve. Reproducibility in the heating and cooling cycles during annealing is considered essential and calibration of each TLD batch may be necessary in critical situations.

C.2 Calcium Fluoride, Doped with Thulium

Calcium fluoride comes in several forms for use in TL dosimetry, but the form of interest for space dosimetry applications is CaF_2:Tm, known as TLD-300®. The material is generally considered to be reusable without any thermal annealing treatments if used for absorbed doses <200 mGy, although annealing at >400 °C for at least 30 min is recommended for low-dose (<30 mGy) applications (McKeever *et al.*, 1995).

The TLD-300® glow curve is shown in Figure C.5. As with LiF, the glow curve consists of multiple overlapping peaks. The main signals used in dosimetry are Peak 3, and Peaks (5 + 6) together (Figure C.5b). The gamma-ray dose response shows linear behavior for Peak 3 up to ~10 Gy, followed by saturation. Peak 5, however, shows linearity up to ~1 Gy, followed by supralinearity, with maximum supralinearity at $\sim 10^5$ Gy. This difference in behavior in the responses of Peaks 3 and 5 to gamma-ray dose results in a markedly different behavior for charged-particle irradiation. Specifically, the ratio of Peaks (5 + 6) to Peak 3 increases with increasing LET, as Figure C.6 illustrates for the TLD-300® glow curve after irradiation

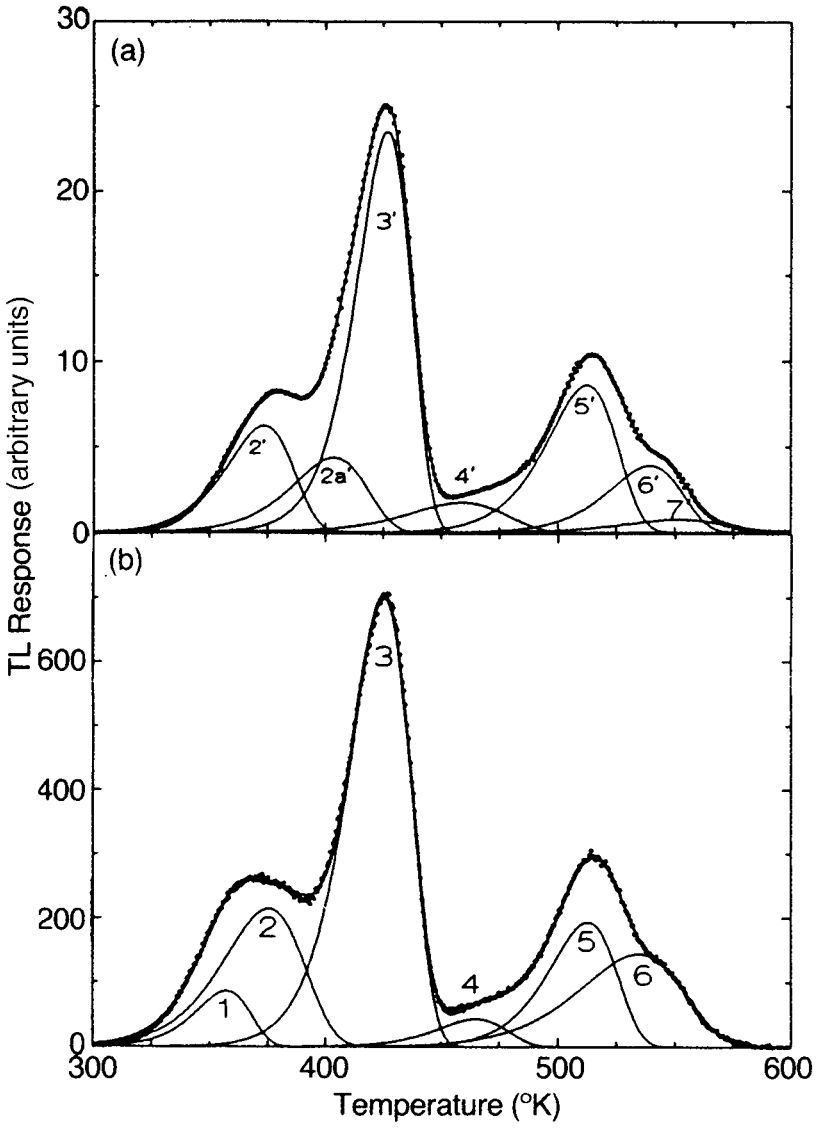


Fig. C.5. Two glow curves from TLD-300®, analyzed using either (a) seven peaks, or (b) six peaks. The six-peak structure is usually adopted in dosimetry (Bos and Dielhof, 1991).

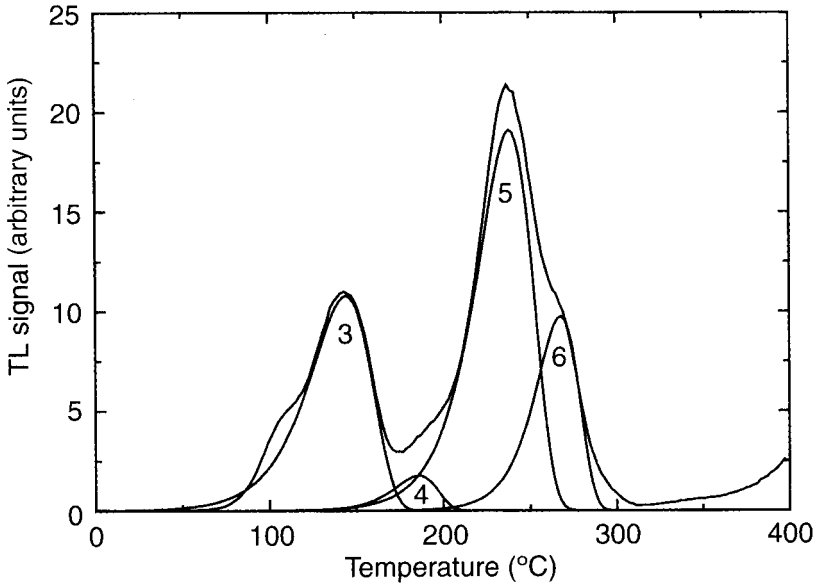


Fig. C.6. TLD-300® glow curve following irradiation with ^{241}Am alpha particles (Buenfil *et al.*, 1999).

with ^{241}Am alpha particles. The variation in the heights of the glow peaks with increasing LET is shown in Figure C.7.

It is clear that the peak-height ratio [Peaks (5 + 6)/Peak 3] is a sensitive indicator of LET of the charged-particle field to which the sample is exposed. The efficiency with respect to gamma-ray irradiation $\varepsilon(L)$ decreases with increasing LET in a similar fashion to that for LiF. The effect of different Z on the efficiency curve has not been studied, nor has the universality of the response yet been thoroughly investigated.

C.3 Lithium Fluoride, Doped with Magnesium, Copper and Phosphorus

The glow curve for LiF:Mg,Cu,P is shown in Figure C.8. The main peak shows a linear response to gamma-ray irradiation, up to ~10 Gy, without any supralinearity. For high-LET charged-particle irradiation the glow curve shows very low sensitivity (approximately a factor of 100 lower than LiF:Mg,Ti) with a pronounced higher temperature peak (Peak 5) compared with the main dosimetry peak

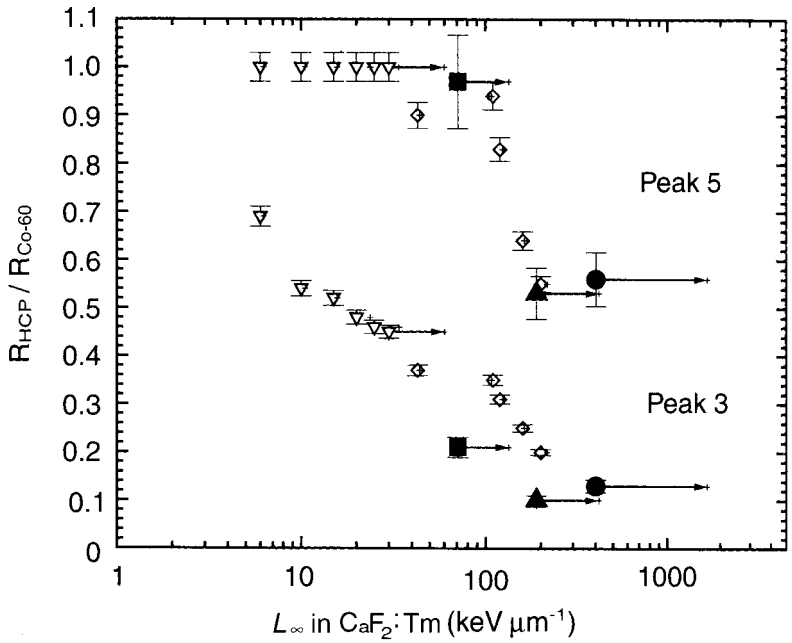


Fig. C.7. Variation in the heights of Peaks 3 and 5, normalized to the heights of these peaks after ^{60}Co gamma-ray irradiation, for various heavy charged particles (HCP) ($R_{HCP}/R_{Co\text{-}60}$). The arrows indicate the entrance and exit LET values for the particles indicated. (∇) helium ions, (◇) neon ions, (■) 0.7 MeV protons, (▲) 5.3 MeV alpha particles, (●) 120 MeV ^{12}C ions. The maximum fluence was 10^{11} particles cm^{-2} (Buenfil *et al.*, 1999).

(Peak 4 in Figure C.8.) The low sensitivity is a result of the microdosimetric distribution of trapped charge along the track of the charged particle and the rapid saturation of the TL signal at high ionization densities (Horowitz and Stern, 1990). The sensitivity to gamma rays and low-LET irradiations, however, is considerably higher than that of LiF:Mg,Ti. Thus, this material acts as an efficient discriminator in mixed low- and high-LET fields. However, a detailed study of the $\varepsilon(L)$ function for this material has not yet been performed.

C.4 Aluminum Oxide, Doped with Carbon

Figure C.9 shows the glow curve for Al_2O_3:C irradiated by gamma rays. The main peak shows a linear response to gamma-ray irradiation, up to ~50 Gy, without any significant supralinearity. The

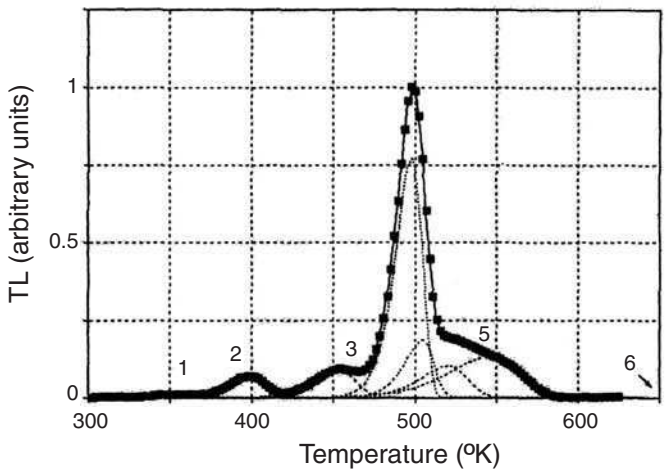


Fig. C.8. Glow curve from gamma-ray irradiated LiF:Mg,Cu,P (McKeever *et al.*, 1993).

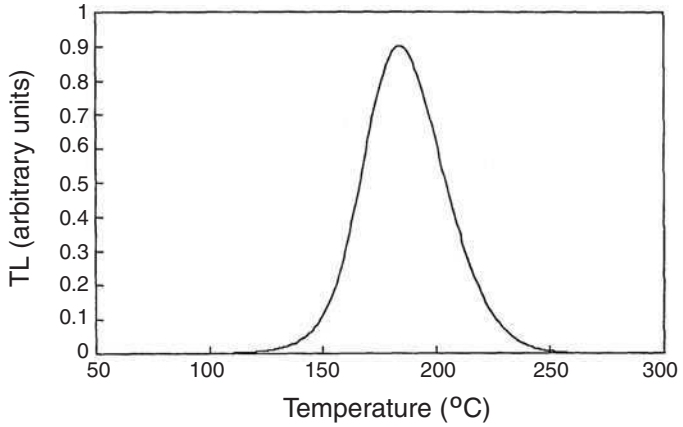


Fig. C.9. Glow curve from gamma-ray irradiated Al_2O_3:C.

efficiency of Al_2O_3:C for the detection of gamma rays is claimed to be as high as 40 to 50 with respect to LiF:Mg,Ti (McKeever *et al.*, 1995). Under alpha-particle irradiation, the main peak saturates at about the same level, but a smaller, higher temperature peak near 325 °C grows linearly, then supralinearly, before saturation (Moscovitch *et al.*, 1993). The TL efficiency ε to alpha particles, with respect to gamma rays, is more than an order of magnitude less for Al_2O_3:C compared to LiF:Mg,Ti (Mukherjee and Lucas, 1993). This

is consistent with the differences observed in the gamma-ray dose response and suggests that this material (like LiF:Mg,Cu,P) would be very effective at discriminating against high-LET particles in mixed low-LET/high-LET fields.

A disadvantage of Al_2O_3:C for TL dosimetry is an observed heating rate dependence due to thermal quenching of the luminescence efficiency (Akselrod *et al.*, 1998). This disadvantage can be overcome, however, by using this material as an OSLD instead of a TLD. Here one measures the radiation-induced luminescence signal using light from a laser beam to stimulate the luminescence. Several OSL readout modes have been suggested and successfully developed (Akselrod and McKeever, 1999; Botter-Jensen *et al.*, 1997).

A complete description of $\varepsilon(L)$, using either TL or optically stimulated luminescence, for this material is not yet available.

C.5 Evaluation of Absorbed Dose and Dose Equivalent

C.5.1 *Equivalent Gamma-Ray Dose*

For a linear growth of a TL signal with gamma-ray dose (from ^{60}Co or ^{137}Cs):

$$\mathrm{TL}_\gamma = \xi\, D_\gamma, \tag{C.2}$$

where ξ is a proportionality constant describing the efficiency of TL production for gamma-ray irradiation (in TL units per unit gamma-ray dose). For linear growth of TL with absorbed dose from a particle with linear energy transfer L:

$$\mathrm{TL}_L = \varepsilon\, \xi\, D, \tag{C.3}$$

with $\varepsilon \leq 1$.

For a mixed particle field of fluence $\Phi(L)$, the delivered absorbed dose to TLD is $\int D(L)\mathrm{d}L$, summed over all angles and all times. Here, D is the absorbed dose delivered to TLD by particles of linear energy transfer L and is a function of L. Thus:

$$\mathrm{TL}_L = \xi \int \varepsilon(L)\, D(L)\, \mathrm{d}L. \tag{C.4}$$

The desired quantity at this stage is $D = \int D(L)\, \mathrm{d}L$. The difficulty is that TL_L is a single number whereas $\varepsilon(L)$ and $D(L)$ are functions. Thus, the problem is "ill-posed." The simplest, and least satisfactory, solution is to determine that gamma-ray dose which gives rise to the same TL signal as that due to the particle irradiation. That is,

one uses D_γ for the absorbed dose in TLD due to the charged-particle field, where:

$$D_\gamma = \int \varepsilon(L)\, D(L)\, \mathrm{d}L. \tag{C.5}$$

C.5.2 *Mean, or Effective, Linear Energy Transfer*

An improved approach is to independently measure the LET fluence spectrum [$\Phi(L)$] and obtain an effective efficiency ($\bar{\varepsilon}$) determined from either a mean or an effective LET ($\overline{L}_i$) suitably averaged over some i. For example, from the known $\Phi(L)$ one can obtain a dose-averaged LET, thus:

$$\overline{L}_D = \frac{\int D(L)\, L\, \mathrm{d}L}{\int D(L)\, \mathrm{d}L}, \tag{C.6}$$

or a fluence-averaged LET, thus:

$$\overline{L}_\Phi = \frac{\int \Phi(L)\, L\, \mathrm{d}L}{\int \Phi(L)\, \mathrm{d}L}. \tag{C.7}$$

One can use the value of $\overline{L}_i$ to determine $\bar{\varepsilon}$ from an experimentally measured function $\varepsilon(L)$ for the specific TLD being used. Alternatively, one can define a mean efficiency from:

$$\bar{\varepsilon} = \frac{\int \varepsilon(L)\, D(L)\, \mathrm{d}L}{\int D(L)\, \mathrm{d}L}, \tag{C.8}$$

using an experimentally measured $\varepsilon(L)$ curve (*e.g.*, Figure C.4). Using $\bar{\varepsilon}$, one then approximates Equation C.5, thus:

$$D_\gamma = \int \varepsilon(L)\, D(L)\, \mathrm{d}L \approx \bar{\varepsilon} \int D(L)\, \mathrm{d}L, \tag{C.9}$$

and obtains the equivalent gamma-ray dose delivered by the particle field from:

$$D = \frac{D_\gamma}{\bar{\varepsilon}}. \tag{C.10}$$

An effective LET for TL can also be evaluated using either the LiF or CaF_2 glow curves. Since the TL glow curve from a mixed particle field can be viewed as the superposition of TL glow curves due to individual particles [*i.e.*, $\mathrm{TL} = \int \mathrm{TL}(L)\, \mathrm{d}L$] then one may use, for example, the LiF (TLD-100®) glow curve to determine the HTR value for the mixed particle space radiation field and compare this with Figure C.3 to arrive at an "effective" LET ($\overline{L}_{\mathrm{TLD}}$) (Schoner *et al.*,

1999; Vana *et al.*, 1996). The glow curve from CaF_2 (TLD-300®) (Figure C.7) can be used in the same way. A question arises, however, concerning how well the effective LET calculated in this way compares with the mean LET calculated using Equations C.6 or C.7. Yasuda and Fujitaka (2000) demonstrate considerable differences between $\overline{L}_{TLD}$ and $\overline{L}_D$ (4.6 and 14 keV μm^{-1}, respectively) using a typical space radiation field spectrum as estimated from data from a TEPC (Badhwar *et al.*, 1996a). Nevertheless, using an effective LET value determined in this way, one can also determine an effective efficiency ε_{TLD} from the known $\varepsilon(L)$ function and estimate the equivalent gamma-ray dose using Equation C.9.

C.5.3 *Dose Equivalent*

The quantity of interest is H (in sievert) determined from:

$$H = Q\,D. \tag{C.11}$$

Q is a function of LET and for a spectrum of charged particles in a mixed particle field:

$$H = \int Q(L)\,D(L)\,\mathrm{d}L. \tag{C.12}$$

Using the calculated equivalent gamma-ray dose in TLD (Equation C.9), H can be approximated by:

$$H_i \approx \overline{Q}_i \int D(L)\,\mathrm{d}L = \overline{Q}_i\,D = \overline{Q}_i\,\frac{D_\gamma}{\overline{\varepsilon}}, \tag{C.13}$$

where the subscript i refers to either D (dose-averaged) or Φ (fluence-averaged), and $\overline{Q}_i$ can be determined from ICRP (1991) using the mean or effective LET value ($\overline{L}_i$) determined from one of the above methods.[12]

[12] From an analysis based on photon interaction coefficients, tabulations of electron and proton stopping powers, and data on muon stopping powers, it is concluded that for a ^{137}Cs calibration in terms of tissue kerma, the TLDs (LiF) will give an estimate of absorbed dose to a small mass of tissue for all low-LET components to within five percent. The energy ranges taken into account include the majority of the low-LET contributions to dose—for photons up to 10 MeV there would be less than a five percent overestimate; for electrons up to 50 MeV, an estimate within two percent; for protons from a few MeV up to 2 GeV an estimate within two percent if only coulomb interactions are considered; for the cosmic radiation secondary muon spectrum, there would be an underestimate of about five percent. In these calculations, it was assumed that the relative light conversion efficiencies for energy deposition by these radiations in the ^{7}LiF:Mg,Ti remained close to unity (Bartlett *et al.*, 2000).

Using the TEPC fluence data of Badhwar *et al.* (1996a) one gets $\overline{Q}_{TLD} = 1.3$ if one uses $\overline{L}_{TLD}$ from the LiF HTR method, or $\overline{Q}_D = 2.5$ if one uses $\overline{L}_D$ calculated directly from the TEPC data (Yasuda and Fujitaka, 2000). However, difficulties with such comparisons arise if there is a significant neutron component and if LiF has a low response to these components, and/or there is a different secondary charged-particle spectrum compared to that in tissue.

Yasuda (2001) combined LET dependencies of the low temperature and high temperature TL peaks from TLD-700® to provide a function $\varepsilon_{HL}(L)$ to mimic the $Q(L)$ function and thereby calculate H from:

$$H = (1 + \eta)\, X_{HT} - \eta\, X_{LT}, \tag{C.14}$$

when

$$\varepsilon_{HL}(L) = (\eta + 1)\, \varepsilon_{HT}(L) - \eta\, \varepsilon_{LT}(L), \tag{C.15}$$

where $\varepsilon_{HL}(L)$ and $\varepsilon_{LT}(L)$ are the TL efficiencies of the high temperature (HT) and low temperature (LT) peaks, respectively; X_{HT} and X_{LT} are the TL values for the high temperature and low temperature TL glow peaks, respectively; and η is an empirically determined constant selected to satisfy the relationship $\varepsilon_{HL}(L) \approx Q(L)$ over the entire range of L. There are difficulties associated with this approach if there is a significant neutron component of the radiation field.

An alternate approach is to limit the use of TLDs to the measurement of absorbed dose from the low-LET ($<$10 keV μm^{-1}) region for which $Q = 1$. In this region, $H = QD = D$. To do so one needs to employ a TLD material with excellent discrimination between high- and low-LET particles. As already described, LiF:Mg,Cu,P or Al_2O_3:C may be suitable, but LiF:Mg,Ti or CaF_2:Tm would be unsuitable. One should still take account of differences between absorbed dose to TLD and absorbed dose to tissue.

To determine H from the high-LET region of the incident field spectrum one could use a PNTD. Thus, if information is available about the LET spectrum $\Phi(L)$, then one can calculate H from $H = \int D(L)\, Q(L)\, dL$ (Appendix D) and the total H would then be given by a combination of TLDs and PNTDs, thus:

$$H = (DQ)_{TLD} + \left[\int D(L)\, Q(L)\, dL\right]_{PNTD} \tag{C.16}$$

To provide the best discrimination between the low- and high-LET regions of the incident spectrum, PADC/CR-39® would be a suitable

PNTD material. Since there would be some overlap between the two detectors each device (TLD and PNTD) would have to be fully characterized as a function of LET and corrections made to avoid "double counting" the absorbed dose in the overlapping region.

Appendix D

Plastic Nuclear Track Detectors

D.1 Description of Method

PNTDs register charged particles by means of etchable damage to the detector structure. The damage trail in a material, which constitutes a charged-particle track, is a result of local deposition of energy during the passage of the particle and as such may be related to restricted LET (L_Δ) or to lineal event density (Paretzke, 1977) or to radial dose (Butts and Katz, 1967) (see also discussion of Paretzke, 1982). The damage is generally permanent but may be partly repaired or may be modified over time, influenced by factors such as temperature, humidity, and the local presence of oxygen or other gases. The particle tracks, the damage "trails," may be viewed directly with an electron microscope in some instances (Price and Walker, 1962; Silk and Barnes, 1959) or may be rendered visible under an optical microscope by etching with a suitable solvent (Young, 1958). The track is developed to form a pit of approximately conical shape by the preferential dissolution along the particle track, with the condition that the track etch rate v_T is greater than the bulk etch rate v_B. The resulting conical etched pits have entrance diameters in the range of a few tenths to a few tens of microns. For an observable track to be formed v_T/v_B must exceed some threshold value and this in turn is related to L_Δ or similar parameter of the particle. The value of v_T/v_B will also determine the maximum "acceptance" angle of incidence for tracks to be made visible. For different particle parameters, the different values of v_T will result in different evolutions of the etched pit shape with time of etching for a given set of etchant parameters (chemical composition, molarity and temperature). The measurement of the dimensions of etched pits and their dependence on etching time allows an estimation to be made

of the charged particle's L_Δ and residual range, and, not always unambiguously, allows identification of particle charge and energy. Stacks of thin sheets of detector material are used to trace the paths of particles. An introduction to the more general study of track etching and its many applications may be found, for example, in Durrani and Bull (1987) and Fleischer *et al.* (1975).

D.2 Neutron Dosimetry

Until the late 1970s, neutron detection using PNTDs was only possible by means of (n,α) or (n,f) reactions and for neutron energies above about 1.5 MeV by the detection of recoil nuclei. The situation changed with the discovery of the proton response of the commonly used plastic, PADC/CR-39®[13] (Cartwright *et al.*, 1978; Cassou and Benton, 1978). Other track etch materials, notably some forms of cellulose nitrate are also able to register protons, but with low sensitivity. Depending on the etch process used, protons of energies up to about 10 MeV may be detected by PADC/CR-39®, corresponding to LETs (in water) down to about 5 keV μm^{-1}.

The application of PADC/CR-39® to neutron personal dosimetry was recognized and demonstrated by several authors (Al-Najjar *et al.*, 1979; Benton *et al.*, 1980; Griffith *et al.*, 1981; Ruddy *et al.*, 1981; Somogyi and Hunyadi, 1980). The addition of a converter layer for the neutron energy region from thermal to a few kiloelectron volts (Bartlett *et al.*, 1986) produces a dosimeter with acceptable energy dependence of response for most practical purposes. The early widespread application however, was hampered by problems of plastic consistency. There have been recent improvements in the methods of material manufacture (Ahmad and Stejny, 1991).

For neutron dosimetry applications, the counting of low track densities can be accomplished for etched tracks in thin films by rapid readout techniques using highly colored detector films or electronically by the development of spark counting. The process of electrochemical etching (Sohrabi, 1974; Tommasino, 1970; Tommasino and Armellini, 1973) greatly increases the size of the etched pits such that they are visible to the unaided eye and can be counted automatically by simple low-power optical systems. In electrochemical etching,

[13] Polyallyl diglycol carbonate is the polymeric form of allyl diglycol carbonate, which is the commercial name for the chemical diethylene glycol bis (allyl carbonate), also known as 2,2′oxydiethylene bis (allyl carbonate) or as the oxydi-2, 1-ethanedyl d-2-propanyl diester of carbonic acid.

a high alternating electric field is applied across the detector foil during chemical etching. The field strengths are typically in the range of 20 to 50 kV_{RMS} cm^{-1} at frequencies in the range 50 Hz to 10 kHz. For pits, which attain a sharply pointed shape as the chemical etching proceeds, the field strength is enhanced at the tip and local breakdown of the material leads to catastrophic damage. The characteristic "tree" shaped formation produced has a diameter in the range of 10 to several hundred microns compared to chemically-etched pit diameters of a few tenths to a few tens of microns. The electrochemically-etched pits are visible to the naked eye and can be counted by simple automated low magnification optical systems. A variation on this process is electro-etching, or "blow up"; in which small pits which have been produced by chemical etching, or relatively underdeveloped pits produced by low-frequency electric field electrochemical etching, or a combination of both, are subjected to a short accelerated high-frequency electro-etch. Electrochemical etching is sometimes preceded by a short chemical etch.

Detailed descriptions of fundamental aspects of neutron dosimetry using PNTDs, including information on the different etch processes and dosimetric characteristics may be found in two review papers (Harrison and Tommasino, 1985; Tommasino and Harrison, 1985), and in a recent survey of the status of development in Europe (Harvey *et al.*, 1998).

D.3 Dosimetry of Cosmic Radiation Fields

PNTDs, in particular, PADC/CR-39®, can be used to determine the neutron and HZE components, and, in part, the proton component of the cosmic radiation field in spacecraft. The material type, and in some cases the batch, needs to be calibrated (see calibration curves, adapted from Keegan, 1996, Figure D.1) either for a sample from the batch used, or by a combination of an *a priori* calibration curve for a material plus an in-flight self-calibration (Gunther *et al.*, 1999; Wiegel *et al.*, 1988). The in-flight self-calibration takes account of changes in sensitivity of the detector owing to flight conditions. Full etch track analysis allows the determination of HZE particle fluence and fluence rate, but is extremely time consuming unless automated. The LET threshold of PADC/CR-39® is in the range 5 to 10 keV μm^{-1}, enabling protons of energy up to about 10 MeV to be detected directly, as well as HZE particles. Secondary charged particles from nuclear (strong force) interactions of higher energy protons and of neutrons, in the detector material itself or surrounding material, are also

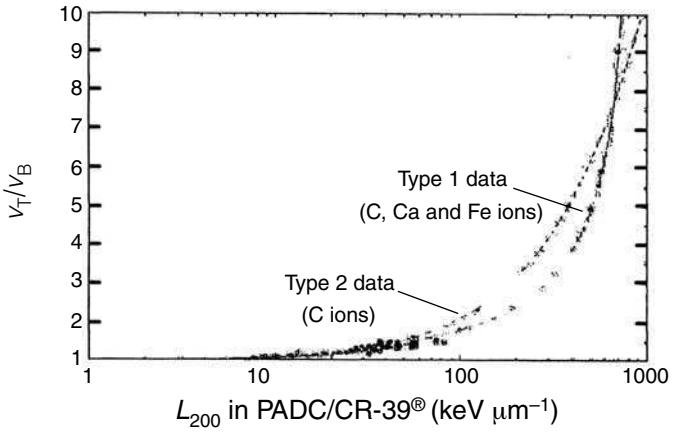


Fig. D.1. Calibration curves for two types of PADC/CR-39® (adapted from Keegan, 1996). L_{200} is the restricted LET (L_Δ; Δ = 200 eV) and v_T/v_B is the track etch rate divided by the bulk etch rate.

detected. The full analysis of the particle track parameters allows the determination of LET spectra (*e.g.,* Figure D.2) (Badhwar *et al.*, 1996a; 1996b; Benton and Parnell, 1988; Doke *et al.*, 1995; Wiegel *et al.*, 1988; Yasuda *et al.*, 2000). The dimensions of a large number of tracks of particles, mostly secondary protons, are measured and their LET determined *via* the calibration curve [samples of PADC/CR-39® are characterized in terms of LET (in water) for proton and heavy charged-particle beams for the LET range from about 5 to 1,000 keV μm^{-1}]. By a measurement of the distribution of absorbed dose (fluence times LET) in LET, H can be determined. The value of H so determined is approximate; the spectrum of secondary charged particles generated in the detector and its immediate surroundings will be different from that for tissue. The known dependence of response of the detector on angle of incidence may be corrected for by assuming that the radiation field is isotropic, or rendered so by the movement of the detector if worn. This assumption must be made with care (for example, Benton and Parnell, 1988). This technique has been successfully applied, for example, to the measurement of H in the radiation field in spacecraft (Doke *et al.*, 1995; Yasuda *et al.*, 2000), in supersonic aircraft at flight altitudes and the European Organisation for Nuclear Research/European Union reference fields (CERF) simulated cosmic radiation neutron field component (O'Sullivan *et al.*, 1999). An example for CERF, a description of which may be found in Hofert and Stevenson (1994), is shown in Figure D.3 (O'Sullivan *et al.*, 1999). An approximation to H from all field components depositing energy with LET greater than

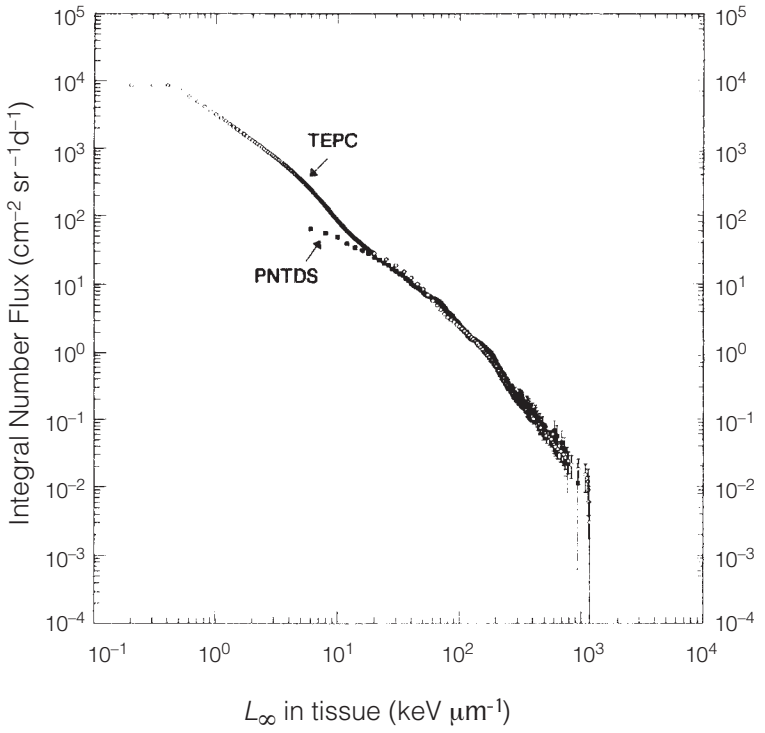


Fig. D.2. LET (L_∞) spectrum for PADC/CR-39® compared with that obtained with TEPC (adapted from Badhwar *et al.*, 1996a).

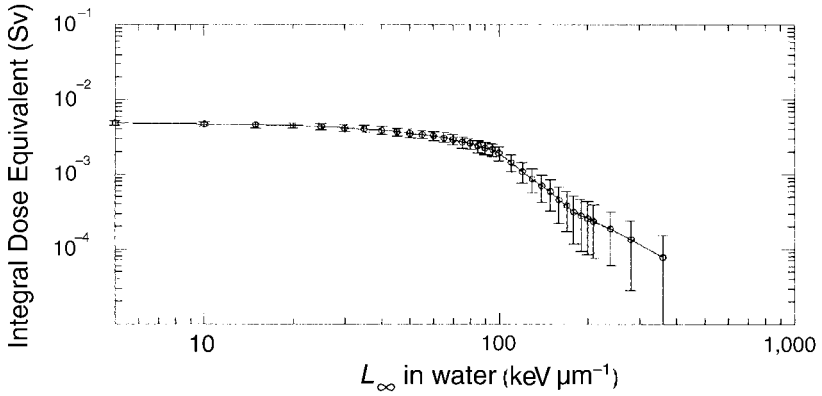


Fig. D.3. Integral dose equivalent as a function of LET (L_∞) for CERF top concrete neutron field, using $Q(L)$ from ICRP (1991) (adapted from O'Sullivan *et al.*, 1999).

5 to 10 keV μm^{-1} is determined by this approach. The contribution from all field components to H for lower values of LET can be determined by passive TLDs or OSLDs.

Another, more approximate approach, is to use a series of different materials each of different LET threshold to obtain particle fluence in a number of LET "bins" (for example, Kopp *et al.*, 1999). Materials that can be used are PADC/CR-39®, cellulose nitrate and polycarbonate (Lexan, Makrofol®).

PNTDs may be used to estimate the higher-LET component of the cosmic radiation field (comprising most of the neutron component, plus the nuclear interaction component of high-energy protons and HZE particles) using the simpler, less time consuming techniques developed for neutron personal dosimetry. Electrochemically etched pits are identified and counted. Readout procedures are fully automated. Figure D.4 shows neutron dose equivalent response data for some operational personal dosimetry systems, three PADC/CR-39® etched track dosimeters [one chemical etch after Fiechtner and Wernli (1999) and two electrochemical etches after Bartlett *et al.* (2001) and Luszik-Bhadra *et al.* (1999)], and one electrochemical etch polycarbonate (Makrofol®) after Jozefowicz *et al.* (1997). The higher energy response data were obtained in quasi-monoenergetic neutron

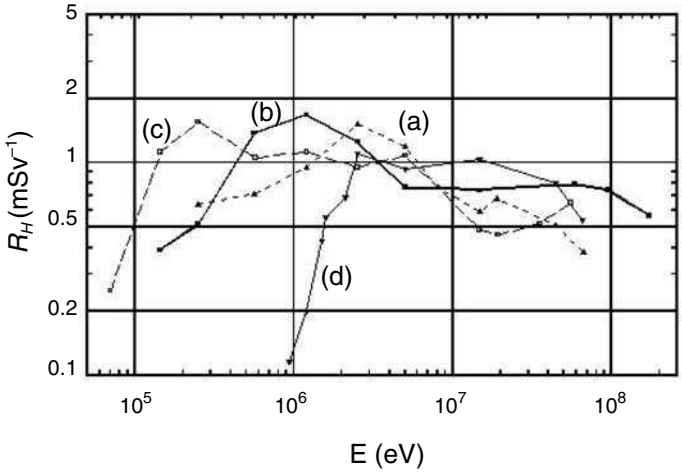


Fig. D.4. Energy dependence of the ambient dose equivalent response (R_H), normalized to unity for americium-beryllium neutrons: for three PADC/CR-39® etched track dosimeters [one chemical etch (a) adapted from Fiechtner and Wernli (1999), two electrochemical etches (b) adapted from Bartlett *et al.* (2001) and (c) adapted from Luszik-Bhadra *et al.* (1999)], and one electrochemical etch polycarbonate (Makrofol®) (d) adapted from Jozefowicz *et al.* (1997).

fields at the Paul Scherrer Institute for the neutron energy range 20 to 70 MeV and at 160 and 180 MeV at the Svedberg Laboratory, Uppsala University. The quasi-monoenergetic fields have about 50 percent of the neutron fluence in the peak and the remainder distributed in approximately uniform lethargy down to thermal (Blomgren, 1997; Schrewe, 1997).[14] The lower energy response must be "stripped off" to obtain the response for the peak neutrons, a procedure that results in significant uncertainties in the high-energy response data. The high-energy response data given in Figure D.4 show reasonable agreement between four different etched track systems. These data are also broadly in agreement with those obtained for high-energy protons (Spurny, 1995). HZE particles will also produce an etchable track and be counted as if produced by a neutron, or neutron-like iterations of high-energy protons, and the same response factor applied (about 5 to 10 μSv per track for a typical electrochemical etch system), which will overestimate the HZE component of H. However, an additional chemical etch allows discrimination.

[14]Blomgren, J. (1997). Personal communication (Svedberg Laboratory, Uppsala University, Uppsala, Sweden);

Schrewe, U.J. (1997). Personal communication (Physikalisch-Techiseche Bundesanstalt, Braunschweig, Germany).

Glossary

absorbed dose (D): The quotient of $\mathrm{d}\bar{\varepsilon}$ by $\mathrm{d}m$, where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted to matter of mass $\mathrm{d}m$, *i.e.*, $D = \mathrm{d}\bar{\varepsilon}/\mathrm{d}m$. The unit for D is joule per kilogram (J kg^{-1}) with the special name gray (Gy).

administrative level: A predetermined reference value of a quantity, below a dose limit, that triggers a specified course of action when the value is exceeded or is expected to be exceeded. In the case of space activities, NASA sets administrative levels for a given mission.

albedo neutrons: Secondary neutrons produced by interactions of galactic cosmic radiation and the atmosphere, and reflected back into space.

as low as reasonably achievable (ALARA): A principle of radiation protection philosophy that requires that exposures to ionizing radiation should be kept as low as reasonably achievable, economic and social factors being taken into consideration. The protection from radiation exposure is ALARA when the expenditure of further resources would be unwarranted by the reduction in exposure that would be achieved. In the case of space activities, ALARA applies to actions taken to keep all doses to the astronauts as low as reasonably achievable, balancing the mission objectives with practical dose reduction steps.

coronal mass ejection: A transient outflow of plasma from or through the solar corona, which may be associated with the generation of solar particle events.

deterministic effects: Effects for which the severity varies with dose and for which a threshold usually exists, *e.g.*, cataracts and skin burns.

dose: A general term used when the context is not specific to a particular dose quantity. When the context is specific, the name or symbol for the quantity is used, *i.e.*, absorbed dose (D), mean absorbed dose (D_{T}), dose equivalent (H), effective dose (E), equivalent dose (H_{T}), or organ dose equivalent ($\overline{H}_{\mathrm{T}}$).

dose equivalent (H): The absorbed dose (D) at a point in tissue, modified by the quality factor (Q) at that point, *i.e.*, $H = QD$. The unit for dose equivalent (H) is the joule per kilogram (J kg^{-1}) with the special name sievert (Sv).

dose limit: A limit on radiation dose that is applied for exposure to individuals or groups of individuals in order to prevent the occurrence of radiation-induced deterministic effects or to limit the probability of radiation related stochastic effects to an acceptable level. For astronauts working in LEO, unique dose limits for deterministic and stochastic effects have been recommended by NCRP.

dosimetry records: The collections of information that document the radiation doses that astronauts receive from space flight, mission-related

aviation activities, mission-related biomedical research, and any other occupational doses. The dosimetry records contain, or are linked to, all the basic information that is necessary to obtain the radiation doses.

effective dose (E): The sum over specified tissues of the products of the equivalent dose in a tissue (H_T) and the weighting factor for that tissue or organ (w_T), *i.e.*, $E = \sum_T w_T H_T$. Effective dose (E) applies only to stochastic effects and is expressed in sievert (Sv).

equivalent dose (H_T): The product of the mean absorbed dose in an organ or tissue (D_T) (*i.e.*, $D_{T,R}$ for a given type of radiation R), and the radiation weighting factor (w_R) that accounts for the relative biological effectiveness of the radiation type. For external exposure, w_R applies to the radiation type incident on the body. When there is more than one type of radiation, the products are summed, *i.e.*, $H_T = \sum_R w_R D_{T,R}$. For space radiation, applies only to stochastic effects and is expressed in sievert (Sv).

fluence (Φ): The quotient of dN by da, where dN is the number of particles incident on a sphere of cross-sectional area da, *i.e.*, $\Phi = \mathrm{d}N/\mathrm{d}a$. The unit for fluence is m^{-2}, commonly given in cm^{-2}. In this Report, distributions of fluence are also noted variously as a function of one or more other variables [*e.g.*, $\Phi(L,t)$, the distribution of fluence as a function of LET (L) and time (t)].

galactic cosmic radiation (GCR): The charged-particle radiation outside the magnetosphere, which comprise two percent electrons and positrons and 98 percent nuclei, the latter component consisting (by fluence) of 87 percent protons, 12 percent helium ions, and 1 percent high atomic number, high-energy (HZE) particles.

gray (Gy): The special name for the unit of absorbed dose (D), kerma and specific energy imparted, 1 Gy = 1 J kg^{-1}.

gray equivalent (Gy-Eq): The name (NCRP, 2000a) for the unit of the quantity gray equivalent (G_T), 1 Gy-Eq = 1 J kg^{-1} [see also gray equivalent (G_T)].

gray equivalent (G_T): The product of D_T and R_i, where D_T is the mean absorbed dose in an organ or tissue and R_i is a recommended value for relative biological effectiveness for deterministic effects for a given particle type i, *i.e.*, $G_T = R_i D_T$. An R_i value applies to the particle type incident on the body. The dose limits for deterministic effects from space radiation are given in the quantity G_T [see also gray equivalent (Gy-Eq)].

high atomic number, high-energy (HZE) particles: Heavy ions having an atomic number greater than that of helium (such as nitrogen, carbon, boron, neon, argon or iron ions that are positively charged) and having high kinetic energy.

immediate dose management: Actions taken to address the potential for high doses from transient events in the space radiation environment that could impact the conduct or completion of the mission or mission tasks. Immediate dose management actions may be taken to avoid exceeding administrative levels or dose limits.

lineal energy (y): The quotient of ε by $\bar{\ell}$, where ε is the energy imparted to the matter in a given volume by a single (energy deposition) event and

$\bar{\ell}$ is the mean chord length of that volume, *i.e.*, $y = \varepsilon/\bar{\ell}$. The unit for lineal energy is J m^{-1}, commonly given in keV μm^{-1}.

linear energy transfer, unrestricted (L or L_∞): The quotient of dE by $d\ell$, where dE is the mean energy lost by the particle, due to collisions with electrons, in traversing a distance $d\ell$, *i.e.*, $L = dE/d\ell$. The unit for linear energy transfer is J m^{-1}, commonly given in keV μm^{-1}. Low linear energy transfer radiations include electrons, x rays, and gamma rays. High linear energy transfer radiations include alpha particles, heavy ions, and interaction products of fast neutrons.

mean absorbed dose (D_T): The mean absorbed dose in an organ or tissue, obtained by integrating or averaging absorbed doses at points in the organ or tissue.

organ dose equivalent ($\overline{H}_T$): The mean dose equivalent for an organ or tissue, obtained by integrating or averaging dose equivalents at points in the organ or tissue. It is the practice in the space radiation protection community to obtain point values of absorbed dose (D) and dose equivalent (H) using the accepted quality factor-LET relationship [$Q(L)$], and then to average the point quantities over the organ or tissue of interest by means of computational models to obtain the organ dose equivalent ($\overline{H}_T$). For space radiations, NCRP adopted the organ dose equivalent as an acceptable approximation for equivalent dose (H_T) for stochastic effects.

personal dosimeter: A radiation detection device worn or carried by an individual to monitor the individual's radiation exposure. For space activities, a device worn or carried by an astronaut in-flight.

quality factor (Q): The factor by which absorbed dose (D) at a point is modified to obtain the dose equivalent (H) at the point, *i.e.*, $H = QD$, in order to express the effectiveness of an absorbed dose (in inducing stochastic effects) on a common scale for all types of ionizing radiation. There is a specified dependence [$Q(L)$] of the quality factor (Q) as a function of the unrestricted linear energy transfer (L) in water at the point of interest.

R_i (recommended value for relative biological effectiveness): A best estimate, for radiation protection purposes, of the relative biological effectiveness for deterministic effects of a given particle type, by which the mean absorbed dose in an organ or tissue (D_T) is modified to obtain gray equivalent (G_T).

radiation safety records: The collections of information that relate to radiation exposure of the astronauts. The radiation safety records consist of multiple sources of information that are linked (*i.e.*, the dosimetry records and their supporting data and files, and other information that bears on the radiation exposure of astronauts).

radiation weighting factor (w_R): A factor used to allow for differences in the biological effectiveness between different radiations when calculating equivalent dose (H_T) (see equivalent dose). These factors are independent of the tissue or organ irradiated.

reentrant electrons: Decay products of unstable nuclei produced by the nuclear interactions of trapped galactic cosmic radiation (GCR) ions.

relative biological effectiveness (RBE): A factor used to compare the biological effectiveness of absorbed doses from different types of ionizing

radiation, determined experimentally. RBE is the ratio of the absorbed dose of a reference radiation (usually taken as 250 kVp x rays) to the absorbed dose of the radiation in question required to produce an identical biological effect in a particular experimental organism or tissue.

sievert (Sv): The special name for the unit of effective dose (E), equivalent dose (H_T), dose equivalent (H), and organ dose equivalent ($\overline{H}_T$), 1 Sv = 1 J kg^{-1}.

solar particle event (SPE): An eruption at the sun that releases a large number of particles (primarily protons) over the course of hours or days.

splash albedo electrons: Electrons scattered upward by interactions in the atmosphere.

stochastic effects: Effects, the probability of occurrence which, rather than their severity, is a function of radiation dose without threshold, *e.g.*, cancer.

tissue weighting factor (w_T): A factor representing the ratio of risk of stochastic effects attributable to irradiation of a given organ or tissue to the total risk when the whole body is irradiated uniformly. The factor is independent of the type of radiation or energy of the radiation.

Acronyms, Abbreviations, and Main Symbols

AE-8	Aerospace Electron Environment, Version 8 (a model of trapped electron radiation)
ALARA	as low as reasonably achievable
AP-8	Aerospace Proton Environment, Version 8 (a model of trapped proton radiation)
CERF	European Organisation for Nuclear Research/ European Union reference field
D	absorbed dose (at a point)
$\dot{D}$	absorbed dose rate (at a point)
D_T	mean absorbed dose in an organ or tissue
DOELAP	U.S. Department of Energy Laboratory Accreditation Program
E	effective dose
E	particle energy
EVA	extravehicular activity (astronaut in space suit outside Space Shuttle or ISS)
FISH	fluorescence *in situ* hybridization
$f(y)$	frequency distribution of lineal energy
G_T	gray equivalent, when used as a quantity
GCR	galactic cosmic radiation
Gy-Eq	gray equivalent, when used as the name of the unit for the quantity G_T
H	dose equivalent (at a point)
H_T	equivalent dose
$\overline{H}_T$	organ dose equivalent
HRE	highly-relativistic electron
HTR	high temperature ratio
HZE	high atomic number, high-energy
ISS	International Space Station
L (or L_∞)	unrestricted linear energy transfer
L_Δ	restricted linear energy transfer
LEO	low-Earth orbit
LET	linear energy transfer
Mir	the Russian orbital space station
n^{-1}	per nucleon
NVLAP	National Voluntary Laboratory Accreditation Program

OSL	optically stimulated luminescence
OSLD	optically stimulated luminescent dosimeter
PADC/CR-39®	polyallyl diglycol carbonate [trade name CR-39 (PPG Industries, Inc., Pittsburgh, Pennsylvania)]
PCC	prematurely condensed chromosome
Φ	fluence
PNTD	plastic nuclear track detector
PSD	position sensitive solid-state detector
Q	quality factor
$Q(L)$	quality factor, as a function of linear energy transfer
R_i	recommended value (best estimate) for relative biological effectiveness of a given particle type i (deterministic effects)
RBE	relative biological effectiveness (experimental)
RHO	radiation health officer
RPL	radiophotoluminescense
SAA	South Atlantic Anomaly
SPE	solar particle event
SRAG	Space Radiation Analysis Group
t	time
TEPC	tissue equivalent proportional counter
TL	thermoluminescence
TLD	thermoluminescent dosimeters
TLD-100®	lithium fluoride, doped with magnesium and titanium (92.5 percent ^{7}Li, 7.5 percent ^{6}Li) (Bicron, Saint-Gobain Industries, Cleveland, Ohio)
TLD-300®	calcium fluoride, doped with thulium (Bicron, Saint-Gobain Industries, Cleveland, Ohio)
TLD-600®	lithium fluoride, doped with magnesium and titanium (enriched to 95.5 percent ^{6}Li) (Bicron, Saint-Gobain Industries, Cleveland, Ohio)
TLD-700®	lithium fluoride, doped with magnesium and titanium (enriched to 99.5 percent ^{7}Li) (Bicron, Saint-Gobain Industries, Cleveland, Ohio)
y	lineal energy
Z	atomic number or particle charge (the atomic number is numerically equal to the electrical charge on the nucleus of a heavy ion)

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The NCRP

The National Council on Radiation Protection and Measurements is a nonprofit corporation chartered by Congress in 1964 to:

1. Collect, analyze, develop and disseminate in the public interest information and recommendations about (a) protection against radiation and (b) radiation measurements, quantities and units, particularly those concerned with radiation protection.
2. Provide a means by which organizations concerned with the scientific and related aspects of radiation protection and of radiation quantities, units and measurements may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations.
3. Develop basic concepts about radiation quantities, units and measurements, about the application of these concepts, and about radiation protection.
4. Cooperate with the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, and other national and international organizations, governmental and private, concerned with radiation quantities, units and measurements and with radiation protection.

The Council is the successor to the unincorporated association of scientists known as the National Committee on Radiation Protection and Measurements and was formed to carry on the work begun by the Committee in 1929.

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SC 1-4 Extrapolation of Risks from Non-Human Experimental Systems to Man
SC 1-7 Information Needed to Make Radiation Protection Recommendations for Travel Beyond Low-Earth Orbit
SC 1-8 Risk to Thyroid from Ionizing Radiation
SC 1-10 Review of Cohen's Radon Research Methods
SC 1-11 Radiation Protection and Measurement for Neutron Surveillance Scanners

SC 1-12 Exposure Limits for Security Surveillance Devices
SC 9 Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV
SC 46 Operational Radiation Safety
SC 46-8 Radiation Protection Design Guidelines for Particle Accelerator Facilities
SC 46-13 Design of Facilities for Medical Radiation Therapy
SC 46-16 Radiation Protection in Veterinary Medicine
SC 46-17 Radiation Protection in Educational Institutions
SC 57-15 Uranium Risk
SC 57-17 Radionuclide Dosimetry Models for Wounds
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SC 64-23 Cesium in the Environment
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SC 87-1 Waste Avoidance and Volume Reduction
SC 87-3 Performance Assessment
SC 87-5 Risk Management Analysis for Decommissioned Sites
SC 89 Nonionizing Electromagnetic Fields
SC 89-3 Biological Effects of Extremely Low-Frequency Electric and Magnetic Fields
SC 89-4 Biological Effects and Exposure Recommendations for Modulated Radiofrequency Fields
SC 89-6 Wireless Telecommunications Safety Issues for Building Owners and Managers
SC 91 Radiation Protection in Medicine
SC 91-1 Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides
SC 91-2 Radiation Protection in Dentistry
SC 92 Public Policy and Risk Communication
SC 93 Radiation Measurement and Dosimetry

In recognition of its responsibility to facilitate and stimulate cooperation among organizations concerned with the scientific and related aspects of radiation protection and measurement, the Council has created a category of NCRP Collaborating Organizations. Organizations or groups of organizations that are national or international in scope and are concerned with scientific problems involving radiation quantities, units, measurements and

effects, or radiation protection may be admitted to collaborating status by the Council. Collaborating Organizations provide a means by which the NCRP can gain input into its activities from a wider segment of society. At the same time, the relationships with the Collaborating Organizations facilitate wider dissemination of information about the Council's activities, interests and concerns. Collaborating Organizations have the opportunity to comment on draft reports (at the time that these are submitted to the members of the Council). This is intended to capitalize on the fact that Collaborating Organizations are in an excellent position to both contribute to the identification of what needs to be treated in NCRP reports and to identify problems that might result from proposed recommendations. The present Collaborating Organizations with which the NCRP maintains liaison are as follows:

Agency for Toxic Substances and Disease Registry
American Academy of Dermatology
American Academy of Environmental Engineers
American Academy of Health Physics
American Association of Physicists in Medicine
American College of Medical Physics
American College of Nuclear Physicians
American College of Occupational and Environmental Medicine
American College of Radiology
American Dental Association
American Industrial Hygiene Association
American Institute of Ultrasound in Medicine
American Insurance Services Group
American Medical Association
American Nuclear Society
American Pharmaceutical Association
American Podiatric Medical Association
American Public Health Association
American Radium Society
American Roentgen Ray Society
American Society for Therapeutic Radiology and Oncology
American Society of Health-System Pharmacists
American Society of Radiologic Technologists
Association of University Radiologists
Bioelectromagnetics Society
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Conference of Radiation Control Program Directors, Inc.
Council on Radionuclides and Radiopharmaceuticals
Defense Threat Reduction Agency
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Society for Risk Analysis
Society of Chairmen of Academic Radiology Departments
Society of Nuclear Medicine
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U.S. Department of Housing and Urban Development
U.S. Department of Labor
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U.S. Environmental Protection Agency
U.S. Navy
U.S. Nuclear Regulatory Commission
U.S. Public Health Service
Utility Workers Union of America

The NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

Another aspect of the cooperative efforts of the NCRP relates to the Special Liaison relationships established with various governmental organizations that have an interest in radiation protection and measurements. This liaison relationship provides: (1) an opportunity for participating organizations to designate an individual to provide liaison between the organization and the NCRP; (2) that the individual designated will receive copies of draft NCRP reports (at the time that these are submitted to the members of the Council) with an invitation to comment, but not vote; and (3) that new NCRP efforts might be discussed with liaison individuals as appropriate, so that they might have an opportunity to make suggestions on new studies and related matters. The following organizations participate in the Special Liaison Program:

Australian Radiation Laboratory
Bundesamt für Strahlenschutz (Germany)

Canadian Nuclear Safety Commission
Central Laboratory for Radiological Protection (Poland)
China Institute for Radiation Protection
Commisariat à l'Energie Atomique
Commonwealth Scientific Instrumentation Research Organization (Australia)
European Commission
Health Council of the Netherlands
International Commission on Non-Ionizing Radiation Protection
Japan Radiation Council
Korea Institute of Nuclear Safety
National Radiological Protection Board (United Kingdom)
Russian Scientific Commission on Radiation Protection
South African Forum for Radiation Protection
World Association of Nuclear Operations

The NCRP values highly the participation of these organizations in the Special Liaison Program.

The Council also benefits significantly from the relationships established pursuant to the Corporate Sponsor's Program. The program facilitates the interchange of information and ideas and corporate sponsors provide valuable fiscal support for the Council's program. This developing program currently includes the following Corporate Sponsors:

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American Podiatric Medical Association
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The NCRP seeks to promulgate information and recommen-dations based on leading scientific judgment on matters of radiation protection and measurement and to foster cooperation among organizations concerned with these matters. These efforts are intended to serve the public interest and the Council welcomes comments and suggestions on its reports or activities from those interested in its work.

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25	*Measurement of Absorbed Dose of Neutrons, and of Mixtures of Neutrons and Gamma Rays* (1961)
27	*Stopping Powers for Use with Cavity Chambers* (1961)
30	*Safe Handling of Radioactive Materials* (1964)
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Volume XXVIII. NCRP Reports Nos. 131, 132, 133
Volume XXIX. NCRP Reports Nos. 134, 135, 136, 137

(Titles of the individual reports contained in each volume are given above.)

NCRP Commentaries

No.	Title
1	*Krypton-85 in the Atmosphere—With Specific Reference to the Public Health Significance of the Proposed Controlled Release at Three Mile Island* (1980)
4	*Guidelines for the Release of Waste Water from Nuclear Facilities with Special Reference to the Public Health Significance of the Proposed Release of Treated Waste Waters at Three Mile Island* (1987)
5	*Review of the Publication, Living Without Landfills* (1989)
6	*Radon Exposure of the U.S. Population—Status of the Problem* (1991)
7	*Misadministration of Radioactive Material in Medicine—Scientific Background* (1991)
8	*Uncertainty in NCRP Screening Models Relating to Atmospheric Transport, Deposition and Uptake by Humans* (1993)
9	*Considerations Regarding the Unintended Radiation Exposure of the Embryo, Fetus or Nursing Child* (1994)
10	*Advising the Public about Radiation Emergencies: A Document for Public Comment* (1994)
11	*Dose Limits for Individuals Who Receive Exposure from Radionuclide Therapy Patients* (1995)
12	*Radiation Exposure and High-Altitude Flight* (1995)
13	*An Introduction to Efficacy in Diagnostic Radiology and Nuclear Medicine (Justification of Medical Radiation Exposure)* (1995)
14	*A Guide for Uncertainty Analysis in Dose and Risk Assessments Related to Environmental Contamination* (1996)
15	*Evaluating the Reliability of Biokinetic and Dosimetric Models and Parameters Used to Assess Individual Doses for Risk Assessment Purposes* (1998)

Proceedings of the Annual Meeting

No.	Title
1	*Perceptions of Risk*, Proceedings of the Fifteenth Annual Meeting held on March 14-15, 1979 (including Taylor Lecture No. 3) (1980)
3	*Critical Issues in Setting Radiation Dose Limits*, Proceedings of the Seventeenth Annual Meeting held on April 8-9, 1981 (including Taylor Lecture No. 5) (1982)
4	*Radiation Protection and New Medical Diagnostic Approaches,* Proceedings of the Eighteenth Annual Meeting held on April 6-7, 1982 (including Taylor Lecture No. 6) (1983)

5 *Environmental Radioactivity,* Proceedings of the Nineteenth Annual Meeting held on April 6-7, 1983 (including Taylor Lecture No. 7) (1983)

6 *Some Issues Important in Developing Basic Radiation Protection Recommendations*, Proceedings of the Twentieth Annual Meeting held on April 4-5, 1984 (including Taylor Lecture No. 8) (1985)

7 *Radioactive Waste*, Proceedings of the Twenty-first Annual Meeting held on April 3-4, 1985 (including Taylor Lecture No. 9) (1986)

8 *Nonionizing Electromagnetic Radiations and Ultrasound,* Proceedings of the Twenty-second Annual Meeting held on April 2-3, 1986 (including Taylor Lecture No. 10) (1988)

9 *New Dosimetry at Hiroshima and Nagasaki and Its Implications for Risk Estimates*, Proceedings of the Twenty-third Annual Meeting held on April 8-9, 1987 (including Taylor Lecture No. 11) (1988)

10 *Radon*, Proceedings of the Twenty-fourth Annual Meeting held on March 30-31, 1988 (including Taylor Lecture No. 12) (1989)

11 *Radiation Protection Today—The NCRP at Sixty Years*, Proceedings of the Twenty-fifth Annual Meeting held on April 5-6, 1989 (including Taylor Lecture No. 13) (1990)

12 *Health and Ecological Implications of Radioactively Contaminated Environments*, Proceedings of the Twenty-sixth Annual Meeting held on April 4-5, 1990 (including Taylor Lecture No. 14) (1991)

13 *Genes, Cancer and Radiation Protection,* Proceedings of the Twenty-seventh Annual Meeting held on April 3-4, 1991 (including Taylor Lecture No. 15) (1992)

14 *Radiation Protection in Medicine,* Proceedings of the Twenty-eighth Annual Meeting held on April 1-2, 1992 (including Taylor Lecture No. 16) (1993)

15 *Radiation Science and Societal Decision Making,* Proceedings of the Twenty-ninth Annual Meeting held on April 7-8, 1993 (including Taylor Lecture No. 17) (1994)

16 *Extremely-Low-Frequency Electromagnetic Fields: Issues in Biological Effects and Public Health,* Proceedings of the Thirtieth Annual Meeting held on April 6-7, 1994 (not published).

17 *Environmental Dose Reconstruction and Risk Implications,* Proceedings of the Thirty-first Annual Meeting held on April 12-13, 1995 (including Taylor Lecture No. 19) (1996)

18 *Implications of New Data on Radiation Cancer Risk*, Proceedings of the Thirty-second Annual Meeting held on April 3-4, 1996 (including Taylor Lecture No. 20) (1997)

19 *The Effects of Pre- and Postconception Exposure to Radiation*, Proceedings of the Thirty-third Annual Meeting held on April 2-3, 1997, Teratology **59**, 181–317 (1999)

20 *Cosmic Radiation Exposure of Airline Crews, Passengers and Astronauts*, Proceedings of the Thirty-fourth Annual Meeting held on April 1-2, 1998, Health Phys. **79**, 466–613 (2000)
21 *Radiation Protection in Medicine: Contemporary Issues*, Proceedings of the Thirty-fifth Annual Meeting held on April 7-8, 1999 (including Taylor Lecture No. 23) (1999)
22 *Ionizing Radiation Science and Protection in the 21st Century,* Proceedings of the Thirty-sixth Annual Meeting held on April 5-6, 2000, Health Phys. **80,** 317–402 (2001)
23 *Fallout from Atmospheric Nuclear Tests—Impact on Science and Society*, Proceedings of the Thirty-seventh Annual Meeting held on April 4-5, 2001, Health Phys. **82**, 573–748 (2002)

Lauriston S. Taylor Lectures

No. Title

1 *The Squares of the Natural Numbers in Radiation Protection by* Herbert M. Parker (1977)
2 *Why be Quantitative about Radiation Risk Estimates?* by Sir Edward Pochin (1978)
3 *Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [Available also in *Perceptions of Risk*, see above]
4 *From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980)
5 *How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [Available also in *Critical Issues in Setting Radiation Dose Limits*, see above]
6 *Ethics, Trade-offs and Medical Radiation* by Eugene L. Saenger (1982) [Available also in *Radiation Protection and New Medical Diagnostic Approaches*, see above]
7 *The Human Environment—Past, Present and Future* by Merril Eisenbud (1983) [Available also in *Environmental Radioactivity*, see above]
8 *Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [Available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations*, see above]
9 *Truth (and Beauty) in Radiation Measurement* by John H. Harley (1985) [Available also in *Radioactive Waste*, see above]
10 *Biological Effects of Non-ionizing Radiations: Cellular Properties and Interactions by Herman P. Schwan (1987) [Available also in Nonionizing Electromagnetic Radiations and Ultrasound*, see above]

11 *How to be Quantitative about Radiation Risk Estimates* by Seymour Jablon (1988) [Available also in *New Dosimetry at Hiroshima and Nagasaki and its Implications for Risk Estimates*, see above]
12 *How Safe is Safe Enough?* by Bo Lindell (1988) [Available also in *Radon*, see above]
13 *Radiobiology and Radiation Protection: The Past Century and Prospects for the Future* by Arthur C. Upton (1989) [Available also in *Radiation Protection Today*, see above]
14 *Radiation Protection and the Internal Emitter Saga* by J. Newell Stannard (1990) [Available also in *Health and Ecological Implications of Radioactively Contaminated Environments*, see above]
15 *When is a Dose Not a Dose?* by Victor P. Bond (1992) [Available also in *Genes, Cancer and Radiation Protection*, see above]
16 *Dose and Risk in Diagnostic Radiology: How Big? How Little?* by Edward W. Webster (1992)[Available also in *Radiation Protection in Medicine*, see above]
17 *Science, Radiation Protection and the NCRP* by Warren K. Sinclair (1993)[Available also in *Radiation Science and Societal Decision Making,* see above]
18 *Mice, Myths and Men* by R.J. Michael Fry (1995)
19 *Certainty and Uncertainty in Radiation Research* by Albrecht M. Kellerer. Health Phys. **69**, 446–453 (1995).
20 *70 Years of Radiation Genetics: Fruit Flies, Mice and Humans* by Seymour Abrahamson. Health Phys. **71**, 624–633 (1996).
21 *Radionuclides in the Body: Meeting the Challenge* by William J. Bair. Health Phys. **73**, 423–432 (1997).
22 *From Chimney Sweeps to Astronauts: Cancer Risks in the Work Place* by Eric J. Hall. Health Phys. **75**, 357–366 (1998).
23 *Back to Background: Natural Radiation and Radioactivity Exposed* by Naomi H. Harley. Health Phys. **79**, 121–128 (2000).
24 *Administered Radioactivity: Unde Venimus Quoque Imus* by S. James Adelstein. Health Phys. **80,** 317–324 (2001).
25 *Assuring the Safety of Medical Diagnostic Ultrasound* by Wesley L. Nyborg. Health Phys. **82**, 578–587 (2002)

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No. Title

1 *The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack*, Proceedings of a Symposium held April 27-29, 1981 (1982)
2 *Radioactive and Mixed Waste—Risk as a Basis for Waste Classification,* Proceedings of a Symposium held November 9, 1994 (1995)

3 *Acceptability of Risk from Radiation—Application to Human Space Flight,* Proceedings of a Symposium held May 29, 1996 (1997)
4 *21st Century Biodosimetry: Quantifying the Past and Predicting the Future,* Proceedings of a Symposium held on February 22, 2001, Radiat. Prot. Dosim. **97**, No. 1, 7–80 (2001)

NCRP Statements

No.	Title
1	"Blood Counts, Statement of the National Committee on Radiation Protection," Radiology **63**, 428 (1954)
2	"Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. **84**, 152 (1960) and Radiology **75**, 122 (1960)
3	*X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements* (1968)
4	*Specification of Units of Natural Uranium and Natural Thorium, Statement of the National Council on Radiation Protection and Measurements* (1973)
5	*NCRP Statement on Dose Limit for Neutrons* (1980)
6	*Control of Air Emissions of Radionuclides* (1984)
7	*The Probability That a Particular Malignancy May Have Been Caused by a Specified Irradiation* (1992)
8	*The Application of ALARA for Occupational Exposures* (1999)
9	*Extension of the Skin Dose Limit for Hot Particles to Other External Sources of Skin Irradiation* (2001)

Other Documents

The following documents of the NCRP were published outside of the NCRP report, commentary and statement series:

Somatic Radiation Dose for the General Population, Report of the Ad Hoc Committee of the National Council on Radiation Protection and Measurements, 6 May 1959, Science, February 19, 1960, Vol. 131, No. 3399, pages 482-486

Dose Effect Modifying Factors In Radiation Protection, Report of Subcommittee M-4 (Relative Biological Effectiveness) of the National Council on Radiation Protection and Measurements, Report BNL 50073 (T-471) (1967) Brookhaven National Laboratory (National Technical Information Service Springfield, Virginia)

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