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:

$$E = \sum_T w_T H_T. \tag{1.1}$$

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.