Space Radiation Dosimetry[i]
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Table of Contents

List of Acronyms

ALARA	=	As Low As Reasonably Achievable
CERN	=	Centre Europeen des Recherches Nucleaires (European Center For Nuclear Research)
CFR	=	Code of Federal Regulations
COTS	=	Commercial Off-The-Shelf
CPD	=	Crew Passive Dosimeter
CPDS	=	Charged Particle Directional Spectrometer
CPU	=	Central Processor Unit
EMU	=	Extravehicular Mobility Unit
EVA	=	Extravehicular Activity
EVCPDS	=	Extravehicular CPDS
GCR	=	Galactic Cosmic Rays
GSFC	=	Goddard Spaceflight Center
ICRP	=	International Commission on Radiation Protection
ISS	=	International Space Station
IVCPDS	=	Intravehicular CPDS
JSC	=	Johnson Space Center
LCD	=	Liquid Crystal Display
LET	=	Linear Energy Transfer
MORD	=	Medical Operations Requirements Document
NCRP	=	National Council on Radiation Protection and Measurements
NSRL	=	NASA Space Radiation Laboratory
PRD	=	Passive Radiation Detector
PSD	=	Position-Sensitive Detector
RAM	=	Radiation Area Monitor
SRAG	=	Space Radiation Analyses Group
TEPC	=	Tissue Equivalent Proportional Counter
TLD	=	Thermoluminescent Dosimeter

1) Background

Astronauts in space are exposed to a radiation environment that can have deleterious health consequences. This environment is both complex (trapped electrons and protons, galactic cosmic ray – GCR -- ions, secondary charged fragments, and neutrons) and dynamic (changing in time and orbital location). The probabilities of adverse health effects – the health risks of space radiation – cannot be measured directly, but must be calculated. The term "dosimetry" is used in the context of space radiation risk management to denote the broad range of measurements required to calculate individual risk probabilities, extending well beyond the traditional reference to absorbed dose as energy locally deposited, to include other properties of radiation thought to be relevant predictors of risk.

Radiation measurements are required to accurately *monitor* astronaut exposures, to operate missions so as not to exceed radiation limits, and to implement the "As Low As Reasonably Achievable (ALARA) principle. They are used to provide *warning* of dangerous changes in the radiation environment. Finally, the information is required to document and provide an *archival* record of each astronaut's radiation exposure history, inform astronauts of their risks, provide evidence that career radiation limits have not been exceeded, and for ongoing and future epidemiological assessments of space flight radiation risks. To the extent that radiation is an important factor in space flight experiments, the data also provide important secondary information related to the interpretation of instrumental readings and experimental results.

The space radiation to which crews are exposed consists of the particles in the environment external to crew quarters and the products of their interactions with planetary or lunar surfaces, residual atmospheres (as on Mars), spacecraft structures and the bodies of crew members; some of these interaction products are neutrons. The complete set of required data are the number, charge, mass, energy and angular distribution of particles. This complete set of data is very difficult to acquire within the typical instrument constraints imposed by space operations; subsets or derivatives of these data are used instead.

2) Radiation Quantities

The most commonly measured parameter is absorbed dose (D)—the energy locally deposited by radiation in a tissue or tissue-like material. Absorbed dose is insufficient by itself to estimate the radiation risk associated with the radiation; it requires a concurrent estimate of the degree to which the deposited energy is concentrated in volumes comparable to the sensitive portions of human cells. The latter is obtained by measuring a quantity related to particle stopping power (dE/dx) and is called linear energy transfer (LET). The two quantities have differed conceptually over the years. Currently, LET is understood to be the energy lost in electronic collisions, and taken to be equal in magnitude to dE/dx. (A detailed discussion of the microscopic patterns of energy

deposition, or "track structure," and of the ways in which they are affected by absorber distribution is beyond the scope of the present discussion.)

A risk-related weighting factor, or average "quality factor" (Q_{ave}), is calculated from a measurement of LET; multiplied by D this leads to the "dose equivalent," the radiation quantity which is compared directly with radiation limits. Both D and LET can also be calculated from the measured particle numbers , energies, and charge. The relationship between Q and LET is defined by national and international radiation protection boards such as the National Council on Radiation Protection and Measurements (NCRP) and International Commission on Radiation Protection (ICRP). The use of Q is well established for converting absorbed dose to cancer risk; use of similar weighting factors for other risks is not as well established.

The dynamic, complex, and unique nature of the space radiation environment is such that radiation health and protection rely upon analytical modeling and continuous measurements of the on-board environment, in addition to the personal dosimetry required to be worn at all times by each crewmember. During missions, the ionizing radiation environment is monitored to provide sufficiently comprehensive and timely data to:

1) maintain crew doses below legal limits and avoid unnecessary levels of exposure in accordance with ALARA requirements;
2) collect and record information used to estimate crewmembers' critical organs and ISS doses for an individual mission and cumulative career records;
3) initiate immediate countermeasures for transient radiation exposure events, e.g., during EVA, solar particle events, or electron belt enhancements.

3) When is a dosimeter not a dosimeter?

Not every measurement leads to a dosimetric result, *i.e.,* data that can be used for the calculation of radiation risk. Such data must have statistical significance given by verifiable accuracy, precision, and sensitivity of the sort that can be traced to accepted standards and procedures, and validated by comparison with instruments using different methods of measurement. Results must have predictive value and not be *ad hoc,* valid only for a special time or circumstance. Finally, results must be of archival quality in order to satisfy record-keeping requirements and allow reinterpretation in terms of new discoveries. Among the questions that need to be answered in the affirmative for such a determination, are:

- Have the instruments been calibrated at a recognized facility?
- Does the calibration site accurately simulate the component of space radiation for which the instrument is designed?
- Can the results of the measurement be interpreted in terms of other measurements?
- Has an intercomparison been performed with other dosimetry instruments?
- Have previous flight data been published in refereed journals?

Similarly, not every dosimetry measurement can necessarily be used for implementing ALARA. In particular, the paradigm of informed consent applies to the assumption of risk, and questions that need to be answered include concerns about individual privacy:

- Are the data available during the mission?
- Are they available in real time?
- Are they available to the crew in flight?
- Is privacy of individual data safeguarded?
- Is there a protocol for use by mission operations?
- Are the data available after the mission?
- Is there a protocol for incorporation into medical records?
- Is there a protocol for interpretation of the data in terms of crew member radiation history?
- Do the data make a relevant contribution to assessments of crew member risk?

4) Biodosimetry[ii]

Biodosimetry is the measurement of biological data for monitoring of radiation exposure and complement the record of accumulated radiation exposure for individuals. It can supplement area monitors in the absence or malfunction of personnel dosimeters, and allows weighing components of environmental radiation according to their biological efficacy. The desired goal is the identification of biological endpoints – "biomarkers" – that can be used as predictors of individual health risks.

There are different types of biodosimeters: *intrinsic biological dosimeters* are used as biomarkers for genetic or metabolic changes; *extrinsic biological dosimeters* are indicators for radiation and other genotoxic substances and agents.

In order to be useful, biodosimeters need to satisfy the following requirements, some of which are similar to requirements for other radiation detectors:

- **sensitivity** to the levels of radiation exposure of concern
- **specificity**: the results are not significantly distorted by individual or circumstantial variations in radiation response
- **accuracy**: predict risk and health care decisions at a *well-defined level of confidence*
- **precision:**; the results are not sensitive to confounding factors (high signal-to-noise ratio)
- **predictive:** there is a plausible *causal* relationship based on testable mechanisms of radiation action, rather than just a contingent *correlation* with radiation exposure

Furthermore, biodosimetry should lead to **diagnostic procedures** that are:

- *practical* under actual circumstances of exposure rather than only under highly restricted laboratory conditions. This places a premium on non-invasive methods.

- *cost-effective* for routine screening; while astronauts constitute a relatively small cohort, extension of biodosimetric information to epidemiological extrapolations may require the study of larger control populations.

Biodosimetry at present is a valuable adjunct, but has not yet developed to the point of being able to replace physical radiation measurements as a primary method of space dosimetry. For this reason, biodosimeters will be discussed separately elsewhere.

5) Classification of radiation measurement instruments used for space dosimetry

The functional requirements for space radiation measurement instruments vary depending on whether they provide integrated data (e.g., "passive" detectors) or time-resolved information ("active," e.g., powered, detectors), and whether the data are used to characterize a radiation environment (area measurements) or an individual dose. Figure 1 illustrates different kinds of instruments used in these different cases.

	PASSIVE	ACTIVE
INDIVIDUAL	• Emulsion • TLD • Nuclear track detectors • Internal Biodosimetry • Radioactivation of tissue • Other chemical or physical latency • Whole body/organ? • Optically simulated luminescence	• Pocket ionization chamber • Protable silicon detectors • High dose or dose rate warning monitors • Whole body/organ? • Direct ion storage
AREA	• Emulsion • TLD • Nuclear track detectors • External Biodosimetry • Induced radioactivity • Other chemical or physical latency • Optically stimulated luminescence • Bonner spheres	• TEPC and similar ionization detectors • Scintillation counters • Particle spectrometers • (Moderated) neutron counters • Portable silicon detectors • Direct ion storage • Bonner spheres

Fig. 1. Radiation Measurement Instrument Classification

The general requirements applicable to instruments can be classified as follows:
- **Accuracy**
  - Calibration, pre-experiment testing, intercomparisons
  - Timing and location
- **Precision**
  - Geometry factors and acceptance
  - Resolution in A ,Z, LET
- **Specificity**
  - No detection artifacts (e.g., response to unintended particles and/or energies, wall effects, kerma vs. dose)
  - Can the measurement be related to an individual exposure?
- **Sensitivity**

- – Signal-to-noise ratio
- – Dynamic range in particles, energies, LET
- – Doses, dose rates and flux
- – Sensitivity adequate for statistically significant results
- ● **Data quality**
  - – Availability: space, ground, on-line, off-line, post-mission (for retrospective studies, data analysis, legal record)
  - – Stability of data, especially for integrating detectors
  - – High duty cycle, so that information is obtained on a time scale comparable to changes in the radiation environment.
  - – Can the data be interpreted in terms of individual risk?
- ● **Life cycle characteristics**
  - – Ease of calibration, testing, maintenance, and repair
  - – Stability of operation
  - – Modular design and subsystem commonality across instruments
  - – Availability of spare units and ease of replacement
  - – Ability to upgrade hardware and software
  - – Complete and accurate hardware and software documentation (drawings, specifications, gate array programs, software source code, etc)

6) Current Capabilities

a) Passive Dosimetry

i) *Passive Radiation Detectors/Radiation Area Monitors:*
Passive Radiation Detectors (PRDs) and Radiation Area Monitors (RAMs) are flown at fixed locations inside the Shuttle crew compartment and habitable volumes of the ISS. PRDs can contain emulsions, TLDs or pocket ionization chambers. Each RAM consists of a small Lexan holder with 24 wells to accommodate the standard commercial TLD chip. Each RAM is loaded with four types of TLD material: LiF (TLD-100), CaF_2 (TLD-300), and Li^6F/Li^7F (TLD-600/700). 6 PRDs are flown during each Shuttle mission—3 located on the middeck and 3 on the flight deck. For ISS support, 16 RAMs are distributed throughout the Service Module, Node 1, U.S. Lab, and Airlock. The PRDs are analyzed at the end of each mission; RAMs are changed out and returned to the ground for analysis with each crew change.

ii) *Crew Passive Dosimeters (CPDs):*
Each Shuttle and ISS crewman is issued a CPD that is kept with them throughout their mission, including during EVAs. With the exception of labeling, the CPDs are identical to the RAMs discussed above.

b) Active Dosimetry

i) *Shuttle Tissue Equivalent Proportional Counter (TEPC):*
Each Shuttle is equipped with a TEPC mounted in a fixed location in the aft starboard portion of the crew compartment middeck. The TEPC measures the lineal energy

transfer spectrum in tissue over the range 0.3-1200 keV/μm and stores this information at nominally 1-minute intervals. The device consists of two components—a detector head (1.78 cm ø x 1.78 cm right cylinder active volume) and spectrometer. The device uses spacecraft power (28V) and must be manually activated/deactivated by the crew. All data is stored the device's solid state memory and downloaded from the instrument following its return to Earth. With no telemetry or alarm capability, the only data access during missions is a small liquid crystal display that allows the crew to observe current dose/dose equivalent rate and accumulated dose/dose equivalent rate.

> ### *ii)   ISS Tissue Equivalent Proportional Counter (TEPC):*
A TEPC is provided as part of the CHeCS Environmental Health System. The ISS TEPC's basic components are the same as those of the Shuttle TEPC, but it also contains many additional features and capabilities necessary for long-term use aboard ISS including: capability to accept 28V or 100V DC input power; 1553B and RS-232 interfaces; audible alarm which activates when dose rates exceed 50 μGy/m; internal test pulser; integral Cm-244 source for monitoring detector gain; capability for ground commanding; capability to upgrade instrument software via uplink; and the ability to be relocated to most ISS modules. The TEPC's 5.08 cm ø x 5.08 cm right cylinder active volume detector head has a volume ~4.5 times greater than the Shuttle version. The TEPC measures the lineal energy transfer spectrum in tissue over the range 0.3-1250 keV/μm and stores this information nominally at 1-minute intervals; an approximation of the dose rate is recorded at 2-sec intervals. The instrument's software design supports cyclic telemetry via the 1553B/S-band system—an approximate absorbed dose and dose equivalent, measurement time, and instrument status are sent via the telemetry stream once per minute and are available for display at the Flight Surgeon, BME, and SRAG consoles in the Mission Control Center.

7) Functional Requirements for Space Radiation Dosimetry[iii]

The use of dosimeters in ISS risk assessment is shown schematically in Fig. 2. Models of the radiation environment are required to estimate the radiation incident on the dosimeters; models of the dosimeter responses are necessary to interpret the dosimeter measurements and account for their inevitable limitations. From a risk assessment perspective, an accurate definition of the radiation field is required at the surface of the body in order to minimize the resulting uncertainty in the absolute risk. Realistically and practically the radiation field cannot be totally specified by a personal dosimeter. Instead, the radiation field is characterized at various locations inside and/or outside the vehicle with area monitors, and various models and analytical techniques are used to extrapolate the measurements to the surface of the astronaut's body. The fewer the number of measurements, the less comprehensive, and/or the further away they are from the crew leads to increasing levels of uncertainty in the risk assessment. In the extreme case no radiation monitors are present, and the risk to each astronaut is based strictly on numerical models of the radiation environment, spacecraft shielding, and charged particle interactions—this leads to the highest uncertainty in the calculated risks. Together, the measurements and theoretical understanding of the radiation fields make it possible to

calculate the organ-level risk as required by the reference to CFR 1960 in the ISS Medical Operations Requirements Document (MORD) .
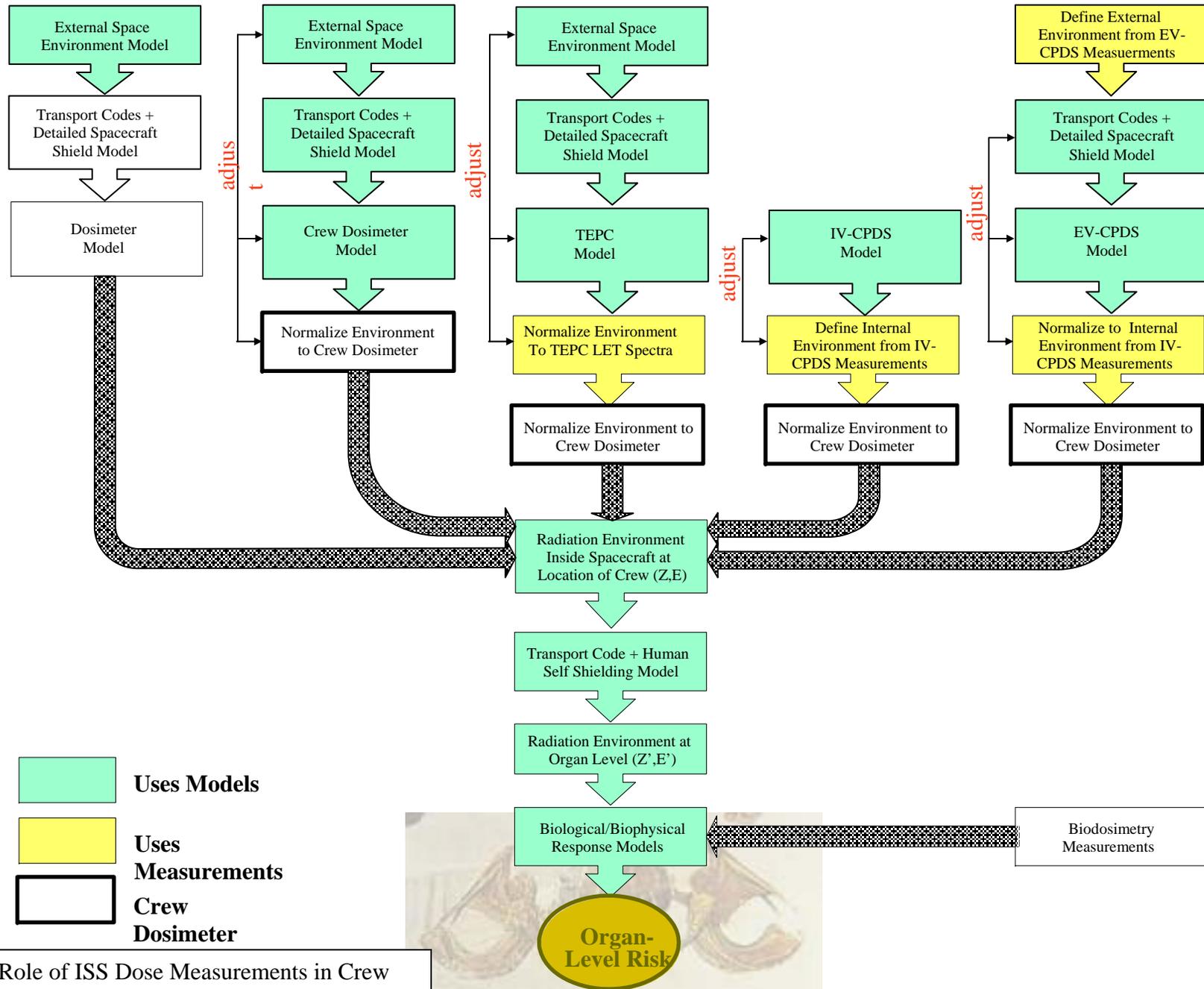
Fig. 2: Role of ISS Dose Measurements in Crew Risk Assessment

The ionizing radiation environment is monitored with passive and active (powered) instruments to document crew exposures, support risk assessments, and to provide data for dose management. The following requirements ensure adequate monitoring of crewmembers' exposure to the very diverse types of space radiation and onboard-radiation producing equipment and radioactive material.

a) Personal Dosimetry Requirements

Each crewmember must be provided with a personal radiation dosimeter for continuous use during a mission. The personal dosimeter serves as the "dosimeter of record," fulfilling a legal requirements to monitor radiation worker exposures. When combined with environmental monitoring and analytical calculations, the personal dosimeter results provide the individual crewmember's exposure record that is used to track against defined exposure limits.

b) Area Dosimetry Requirements

Area monitors are passive or active detectors placed throughout the ISS habitable volume and/or Shuttle crew compartment to provide additional information about the temporal behavior, biological effectiveness ("radiation quality"), and inhomogeneity of the ambient radiation field. External radiation monitors provide near real-time information about the dynamic radiation environment experienced by crewmembers during EVAs, data for use in verifying the various models used to evaluate exposures internal and external to ISS and Shuttle, and measurements to update space radiation climatological models.

i) Passive Radiation Area Dosimetry

Passive dosimeters, capable of measuring time-integrated absorbed dose, must be deployed at designated fixed locations within each pressurized module. Knowledge of the spatial distribution of exposure rate is necessary to identify areas that have a relatively high exposure rate (i.e. avoidance areas) and to reconstruct a crewmember's exposure in the event of a lost or otherwise unrecordable personal dosimeter. Continuous area monitoring is necessary because exposure rates and their distribution throughout the vehicles change with vehicle altitude, attitude, internal vehicle configuration, number and location of modules, position in solar cycle, etc. Passive dosimeters collect data even during situations when power is lost to other instruments.

ii) Active Radiation Area Monitoring

Active radiation area monitors provide continuous information to ground controllers for tracking cumulative crew exposures during missions, identifying areas within the vehicle to avoid due to high dose rates, identifying low dose rate areas to use as "storm shelters," and alerting to enhanced radiation environment conditions. Measurements from various advanced active area monitors are needed to reduce the uncertainty in final calculated crew risk assessments and to support operational practices through verification of numerical ISS shielding model.

(1)   Time-resolved LET or y Spectrum Monitoring
Measured LET spectra, or its surrogate lineal energy (y) spectrum, are
needed to convert the absorbed dose, provided by personal dosimeters, to
the regulatory-required equivalent dose. The LET spectra inside a vehicle
depends on many factors, including the geographic location, local vehicle
mass distribution, space weather conditions, position in the solar cycle,
etc. LET (or y) spectrometers which provide time-resolved measurements
are required to resolve the LET spectra into contributions from radiation
source terms (ie, GCR, trapped protons, solar particle event protons, etc).
Because the LET spectrum is strongly dependent on local shielding, LET
spectrometers need to be portable and capable of reaching most locations
inside the vehicle.

(2)   Internal Time-resolved Charged-Particle Monitoring (ISS only)
Measurement of the time-resolved energy- and direction-dependent
distribution of charge-identified particles inside the vehicle provides the
most accurate radiation source term for computing organ-level exposure
and the resulting risk. All other physical quantities (such as LET spectra
and absorbed dose) are not singular, and therefore result in ambiguity and
hence increased uncertainty in estimates of crew health risk. The
measured charged particle energy spectra also provides definitive
benchmarks for validating analytical models used to compute the radiation
environment inside the vehicle.

(3)   Neutron Monitoring
Radiation monitoring instruments should provide the capability to
characterize the neutron contribution to crew exposures. Results from
scientific research demonstrate that secondary neutrons may contribute 10-
30% of the total radiation effective dose received by astronauts inside a
space vehicle such as ISS. Since neutrons represent an important fraction
of the crew's effective dose, it is necessary that this contribution be
monitored for accurate reporting (as required by agency regulations) and
accurate risk assessment determination. Neutrons can be monitored
directly through neutron spectroscopy. However, because of the technical
difficulties inherent in performing such measurements in the mixed
neutron-charged particle environment behind spacecraft shielding,
measurements designed to accurately measure the contribution of neutrons
to the dose and dose equivalent can be used as a surrogate for direct
neutron spectroscopy.

(4)   External Radiation Area Monitoring
External active radiation area monitoring of trapped protons and GCR
(ISS only) should provide information on the time-resolved direction- and
energy-dependent charged-particle spectra immediately exterior to the
vehicle. Measurements of the external direction- and energy-dependent
charged particle spectra are used with radiation transport codes and

models of the vehicle's mass distribution to calculate the radiation environment inside the vehicle as part of the crew health risk assessment process. In addition, instruments inside the vehicle cannot monitor a significant portion of the external radiation environment that is important to EVA crew exposures.

(5)　　　External Radiation Area Monitoring—Trapped Electrons (ISS only)

The rationale for an external electron dosimeter was described extensively by the National Research Council Report, "Radiation and the International Space Station" (NRC, 2000). The safety concern for crews is the enhancement of the Earth's electron belts following geomagnetic disturbance originating from dynamic solar conditions. Electron fluxes have been observed to increase by more than 10-fold following geomagnetic disturbance lasting for several days to weeks. Although not an issue for internal organ exposures, the enhancement can significantly increase doses to the skin or lens. Distinct dosimetry methods are needed for charged ions and electrons because of the mechanisms of energy deposition. Furthermore, because electrons do not penetrate into the internal vehicle, internal monitors are not adequate to measure increase electron doses to crews. Therefore, an electron measurement capability is needed for electrons over the energy range of 0.5 to 7 MeV. The detector should have a wide acceptance angle, capability to handle high flux rates, and provide a capability to trigger alarms to internal monitors and ground controllers.

c)　　**Radiation Contingency Monitoring Requirements**

High range, high rate dosimeters should be present on board in order to measure high dose-rate contingency events. Extreme space radiation environmental conditions are possible that greatly exceed levels that can be accurately measured by LET or charged particle spectrometers. High rate dosimeters that can be read by the crew are specifically designed to accurately measure under such extreme conditions.

d)　　**Dosimetric Survey Requirements (ISS only)**

i)　　*LET or y Spectrum Survey*

Instrumentation should be relocated every 14 to 21 days to complete surveys of the entire habitable volume once each ISS increment or every 3-6 months. This requirement provides for the possibility to measure LET in different locations using the same instrument. It facilitates inter-comparison with data from other radiation instruments, thereby enhancing the collective value of all data sets. The local radiation environment may change significantly as equipment, stowage items, and consumable items are relocated.

ii)   *Charged-Particle Survey Coverage*

Time-resolved measurements of the energy-and direction-dependent distribution of charge-identified particles should be made in each habitable module. Instrumentation should be capable of surveying the majority of each module.   Charged-particle energy spectra are necessary for validating models of the radiation environment inside a ISS. These data contain sufficient information to estimate crew organ exposures and resulting risk.

e)   Radiation Data Downlink Requirements

The current requirements are principally informed by the perceived needs of ISS use and are probably most directly applicable to ISS operations and experiments. Data downlinks for exploration beyond LEO are likely to require relaying by several stations.

i)   *Internal Charged-particle Data Down-link*

 Detailed data from time-resolved energy- and direction-dependent charged-particle detectors mainly supports real-time flight experiments. It should be down-linked on a time scale that precludes loss of data and supports contingency evaluations. Due to the volume of detailed particle data to be acquired and the finite quantity of instrument data storage onboard, it is necessary to frequently download the charged particle data to a base station to ensure data will not be lost. The detailed particle data will also be used periodically to update the estimated crew cumulative exposure risk.

ii)   *Internal Charged-particle Dose Rate Down-link*

Dose rate from charged-particle monitoring equipment should be continuously transferred to mission controllers for operational evaluation and real-time flight support. The requirement provides flight control personnel with an accurate insight into the radiation environment experienced by the crew, especially during periods of enhanced space environment conditions. Dose rate data transferred to the ground serves as the basis for implementation of immediate dose management actions. Although this requirement is not the primary purpose for charged-particle monitoring equipment, it provides a measure of redundancy for dose rate monitoring.

iii)   *Internal LET or y Spectrum Data Downlink*

Time-resolved data from at least one LET monitoring instrument inside every habitat should be transferred to mission controllers as required for operational evaluation. The requirement provides flight control personnel with an accurate insight into the radiation environment experienced by the crew, especially during periods of enhanced space environment conditions.

iv)   *External Time-Resolved Charged-Particle Data Down-link*

Detailed time-resolved particle spectra should be down-linked on a timescale that precludes loss of data. Due to the volume of detailed particle data that will be acquired, and the finite quantity of instrument data storage, it is

necessary to frequently down-link or download the charged particle data to ensure data will not be lost. The detailed particle data will also be used for periodically updating the estimated crew cumulative exposure risk.

v)   *External Dose Rate Data Down-link*
Dose rate data characterizing the local radiation environment outside the habitat should be continuously transferred to mission controllers for operational evaluation and real-time flight support. The requirement provides flight control personnel with an accurate insight into the status of the external radiation environment, especially during enhanced periods associated with space weather activity. External dose rate data transferred to the ground serves as part of the information used to make EVA go/no-go recommendations.

f)   **Alarm Capability**

At least one onboard active instrument should have the ability to alert the crew when exposure rates exceed a set threshold. An onboard radiation alarm/warning system enables the crew to implement immediate countermeasures for transient high-radiation events. Without an alarm, the crew will not be able to apply immediate countermeasures. Reliance on crew alerts via ground-based monitoring or model predictions requires continuous communication coverage, which is not always available.

8) Operational Requirements

The previous considerations have been discussed in detail within NASA as well as at many international meetings held to establish dosimetry requirements. The consensus of these analyses is expressed in the following ranges of operation:

a)   **Personal Dosimeter Operational Requirements—Dosimeter of Record**

1. Measure the point quantities D, the spectrum D(L), and calculate H to adjacent tissue from radiation environment experienced at surface of astronauts inside a vehicle/module or EMU
   a. Expected radiation environment
      i. Protons: ~10 MeV – 1 GeV
      ii. Electrons: ~ 0.5 MeV – 7 MeV
      iii. HZE (He to Fe): ~ 10 MeV/amu – 10 GeV/amu
      iv. $^1n_0$: TBD
   b. Equivalent depth in tissue
      i. TBD
   c. Sensitivity
      i. Minimum Detectable Dose: 0.1 mGy
      ii. Maximum dose to be measured: 0.4 Gy
      iii. Spectrum coverage of D(L): TBD
      iv. Dose rate: TBD
   d. Measurement accuracy in H_2O or tissue

        i.   D: TBD
      ii.   Spectrum coverage of fluence(L): TBD
     iii.   H: TBD

2. Size/Mass/Volume
   a. Relatively small size/volume and low mass
      i. Should easily fit within a "shirt pocket"
      ii. As a guideline, current personal dosimeter parameters are
         1. mass: TBD
         2. dimensions: TBD
   b. Personal dosimeters need to be compatible with current methods of deployment

3. Power
   a. Preferably, no power should be require
   b. If powered, dosimeter should be capable of running from small, removable batteries for > 180 days

4. Crew Involvement
   a. Preferably, crew involvement with the device should be limited to wearing and occasional testing
   b. If crew time is required, should not exceed 10 minutes/week

5. Shelf-Life
   a. Preferably, device and its components should have an indefinite shelf life
   b. For devices or components with a finite shelf life, shelf life should exceed 3 years

6. Dosimeter Analysis
   a. The dosimeter should not require analysis on-orbit
   b. The permanence of the dosimeter's signal should allow accurate measurements of at least 270 days (dosimeter preparation/assembly to analysis) with less than a 7% reduction in the accuracy of measured dose

7. Spacecraft Environment Compatibility
   a. The dosimeter and its components must meet Shuttle, ISS, Russian Service Module, NASA EMU, and Russian Orlan safety and environmental requirements, including
      i. Operate in a vacuum
      ii. Operate in a 3 p.s.i/100% O_2 environment
      iii. Operate over the temperature range TBD
      iv. Operate at 95% relative humidity with temperatures up to 95 °F
      v. Negligible off-gassing

vi. Cannot include special nuclear materials (e.g., Pu, U)

8. Miscellaneous Requirements
   a. Dosimeter or holder must include unique identification
   b. Dosimeter must include a means for fastening to clothing and to the inside of spacesuit pockets

b) **Operational Requirements for Internal and External Area Dosimeters**

1. Measure the point quantities D, the spectrum D(L), and calculate H to adjacent tissue from radiation environment experienced at surface of astronauts inside a vehicle/module or EMU
   a. Expected radiation environment
      i. Protons: ~10 MeV – 10's of GeV
      ii. Electrons: ~ 0.5 MeV – 7 MeV
      iii. HZE (He to Fe): ~ 10 MeV/amu – 10's of GeV/amu
      iv. $^1n_0$: Thermal (<0.1 MeV) to 10's of GeV
   b. Equivalent depth in tissue
      i. TBD
   c. Sensitivity
      i. Minimum Detectable Dose: 0.1 mGy
      ii. Maximum dose to be measured: 0.4 Gy
      iii. Spectrum coverage of D(L): TBD
      iv. Maximum dose rate: TBD
   d. Measurement accuracy in H_2O or tissue
      i. D: TBD
      ii. Spectrum coverage of fluence(L): TBD
      iii. H: TBD

2. Size/Mass/Volume
   a. Passive area monitors will be identical to personal dosimeters
   b. Active area monitors:
      i. TBD

3. Power
   a. Passive: no power required
   b. Active:
      i. capable of running from small, removable batteries for > 180 days
      ii. compatible with Russian and US power standards

4. Crew Involvement
   a. Preferably, no crew involvement with the device would be required, other than occasional repositioning
   b. If crew time is required, should not exceed 10 minutes/week

5. Shelf-Life

       a. Preferably, device and its components should have an indefinite shelf life

       b. For devices or components with a finite shelf life, shelf life should exceed 3 years

6. Dosimeter Analysis
       a. The dosimeter should not require analysis on-orbit
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              i. Operate in a vacuum
              ii. Operate in a 3 p.s.i/100% O_2 environment
              iii. Operate over the temperature range TBD
              iv. Operate at 95% relative humidity with temperatures up to 95 °F
              v. Negligible off-gassing
              vi. Cannot include special nuclear materials (e.g., Pu, U)

8. Telemetry
9. Miscellaneous Requirements
       a. Dosimeter or holder must include unique identification
       b. Dosimeter must include a means for fastening to clothing and to the inside of spacesuit pockets

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[i] Material in this article based on an unpublished report authored together with F. M. Sulzman, M. Golightly, and F. A. Cucinotta. (Radiation Dosimetry Working Group Final Report, September 30, 2003)

ii A detailed discussion of biodosimetry in space may be found in: G. Horneck. Biological monitoring of radiation exposure. Advances in Space Research Volume 22, Issue 12, 1998, Pages 1631-1641. Proceedings of the F2.4 Symposium of COSPAR Scientific Commission F.

For a series of articles discussing biodosimetry in more detail, cf.

Advances in Space Research, Volume 31, Issue 6, March 2003, Pages 1487-1493. Space Life Sciences: Biodosimetry, Biomarkers and Late Stochastic Effects of Space Radiation.

A.L. Brooks. Biomarkers of exposure, sensitivity and disease. Int. J. Radiat. Biol. Vol. 75, No. 12, 1999, pp. 1481-1503

[iii] Measurements of effective dose in space using a life-size human phantom torso in the STS-91 Shuttle-Mir mission, which flew at nearly the same orbit as that of the International Space Station (ISS), with references to earlier work, are described in: H. Yasuda. Effective Dose Measured with a Life Size Human Phantom in a Low Earth Orbit Mission. J. Radiat. Res., 50, 89–96 (2009)