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ESRAS: An Enhanced Solar Radiation Alert System

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16. Abstract

Since 2003, The Federal Aviation Administration has operated a Solar Radiation Alert System to aid the aerospace community and interested members of the flying public in their decision making with regards to solar ionizing radiation. The first alerts were issued during the solar storms of late October 2003. In the years since its initial operation, several improvements have been made to the calculations behind the dose rates and the means of communicating the results to the aerospace community and the flying public. The basic method of satellite data evaluation described in earlier reports remains unchanged, but it has been updated and expanded. This report describes the most recent improvements, as well as those planned for inclusion in the next few years. The recent improvements include: new atmospheric response functions for protons, expansion of calculations to middle and low latitudes, and continuous updating of a global map of the most recent calculations. Other improvements planned include: the addition of solar alpha particle flux to the calculations, corrections for geomagnetic disturbance effects on global dose rates, and corrections for anisotropy based on available neutron monitor data.

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Contents

ESRAS: An Enhanced Solar Radiation Alert System

1. INTRODUCTION 1
2. ENHANCMENTS 1
2.1 Summary of the Previous System 1
2.2 Recent Changes 1
3. FUTURE FEATURES 4
4. REFERENCES 4
APPENDIX A 1
APPENDIX B 5

ESRAS: AN ENHANCED SOLAR RADIATION ALERT SYSTEM

1. INTRODUCTION

During air and space travel, passengers and crew may be exposed to ionizing radiation at higher dose rates than members of the general population. For air travelers and for future space tourists that do not go into orbit, the principal source of ionizing radiation is *galactic cosmic radiation* (See Appendix A for a glossary of radiation related terms). This radiation consists of ions of nearly every element in the periodic table. These ions travel at speeds approaching that of light. This radiation is so highly penetrating that shielding of vehicle occupants and components is impractical with current propulsion technologies. This radiation is also essentially *isotropic* (having the same intensity from all directions) and slowly varies in intensity (typically by about a factor of two) over the course of a *solar cycle* (about 11 years). Because shielding is impractical and dose rates are relatively low (a few to a few tens of microSieverts per hour [μSv/h], depending on altitude, geomagnetic effects, and solar activity), radiation protection strategies for occupants of these vehicles rely on limiting individual cumulative exposures to below recommended limits.

While galactic cosmic radiation is the natural background radiation for flights, occasionally a disturbance in the Sun leads to a large flux of solar protons and alpha particles with sufficient energy to penetrate Earth's magnetic field, enter the atmosphere, and increase ionizing radiation levels at aircraft flight altitudes (*geopotential altitudes* are reported) to levels significantly above galactic cosmic radiation levels. Since 2003, the Aerospace Medical Research Division at the Civil Aerospace Medical Institute (CAMI) of the Federal Aviation Administration (FAA) has maintained and continues development of a solar radiation alert system [Copeland et al., 2005; 2009] to provide information on these events, referred to as *Solar Proton Events* (SPEs), as they occur. This report describes the most recent enhancements, as well improvements planned for inclusion in the next few years.

2. ENHANCMENTS

2.1 Summary of the Previous System

Previous versions of the FAA Solar Radiation Alert (SRA) system continuously evaluated measurements of high-energy protons made by instruments on Geostationary Operational Environmental Satellite (GOES) satellites, operated by the National Oceanic and Atmospheric Administration (NOAA). If measurements indicated the likelihood of a substantial elevation of ionizing-radiation levels at aircraft flight altitudes at polar latitudes (locations with a *vertical cutoff rigidity* of ~0 MV), alert messages were issued to the public through NOAA's Weather Wire Service (NWWS). The specific criteria for issuance of an SRA was that the estimated effective dose rate induced by solar protons at 70,000 ft equaled or exceeded 20 microsieverts per hour (μSv/h) for each of three consecutive 5-minute periods, equivalent to a level 3 event on the D scale [Meier and Mathiä, 2014]. Because of the potential for a delay of 3-20 minutes in communication processes and the three 5-minute periods, notification of the start of alert conditions may have been 18-35 minutes after the start of the first 5-minute period. While alert conditions persisted, updates were sent through the NWWS. The alert was canceled when the average effective dose rate at 70,000 ft remained less than 20 μSv/h for six consecutive 5-minute periods.

2.2 Recent Changes

As the previous alert system did, the Enhanced Solar Radiation Alert System (ESRAS) operates continuously to monitor the potential hazard of increased particulate ionizing radiation from the Sun using GOES data as the basis for the hazard analysis. With respect to sending messages through the NWWS, nothing has been changed, but improvements have been made in the calculations: The solar proton fluence to effective dose conversion coefficients have been recalculated using the final release of the Monte Carlo transport code MCNPX 2.7.0 [ORNL, 2011]; calculations have been expanded from polar latitude to include middle and low latitudes, while still assuming isotropic incident radiation; and a continuously updating global map of the most recent calculations is generated. New data sets are available using the contact information provided in Appendix B.

The tables used to convert proton fluence to effective dose at selected altitudes were recalculated using MCNPX 2.7.0 as part of the development of CARI-7 (FAA software used to calculate flight doses from galactic cosmic radiation) [Copeland, 2014]. The new conversion coefficients are based on considerably more trials and include secondary heavy and light ion transport that was missing in the coefficients calculated using MCNPX 2.6.0.

Previously, the system calculated dose rates at 0 gigavolts (GV) effective vertical cutoff rigidity (i.e., polar latitude) locations. The expansion to middle and low latitudes is based on global calculations of *effective vertical cutoff rigidity* by Smart and Shea using the 2010 International Geophysical Reference Field [Smart and Shea, 2012]. These data, for geomagnetically normal conditions (no geomagnetic storm in progress), are shown in Figure 1. For each calculated location, these effective vertical cutoff rigidities are used as a pass band filter, screening out particles with rigidities below the effective vertical cutoff. During a geomagnetic storm the cutoff rigidities would usually shift towards the equator.

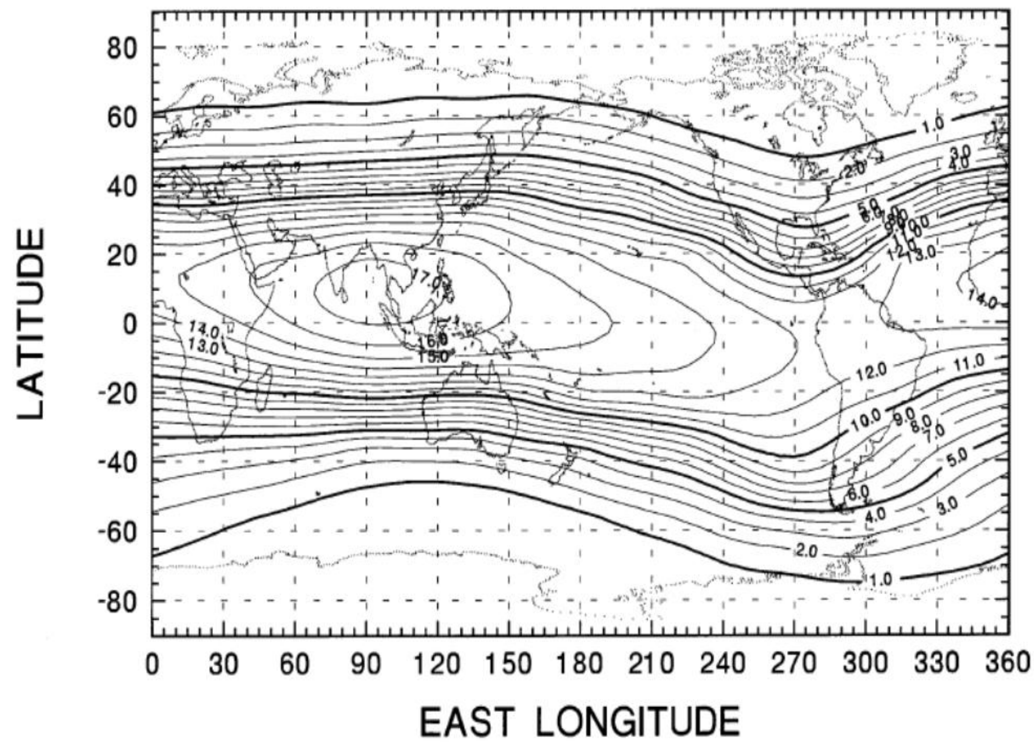

Figure 1. Vertical magnetic cutoff rigidities in GV for the 2010 epoch calculated by Smart and Shea using the IGRF 2010 internal reference field [Smart and Shea, 2012].

The expansion of Web technologies and the FAA's adoption of ArcGIS graphical display software provides an opportunity to share the data on a global scale in a manner accessible by everyone by using a visual, rather than text-based, means of presentation. The new non-zero cutoff data are thus displayed as continuously up-dating maps of dose rate at points of equal effective ver-tical cutoff rigidity along lines of constant geographic longitude, color coded to the D scale at 70,000 ft (flight level 700). Figures 2 and 3, respectively, show what the-se maps look like during normal conditions (all D_{700} = 1 or 0) and during a large solar proton event (D_{700} = 3 or more for some locations). While the specific details may change when full mapping capabilities are added to the FAA's public servers, these maps show the basic layout and what can be done now with ArcGIS Web.

Clicking on an active (colored) point on the map brings up a report of solar dose rates at altitudes from 20,000 ft. to 70,000 ft. for that location.

"When Date: 20150918
UTC 18:25
From GOES-Primary
Lat -30.00
Long -60.00
VertCut (GV) 10
Level 1
Code green
Alt Dose rate (microSv/h)
20000! 0.0000E+00
30000! 0.0000E+00
40000! 0.0000E+00
50000! 0.0000E+00
60000! 0.0000E+00
70000! 0.0000E+00 "

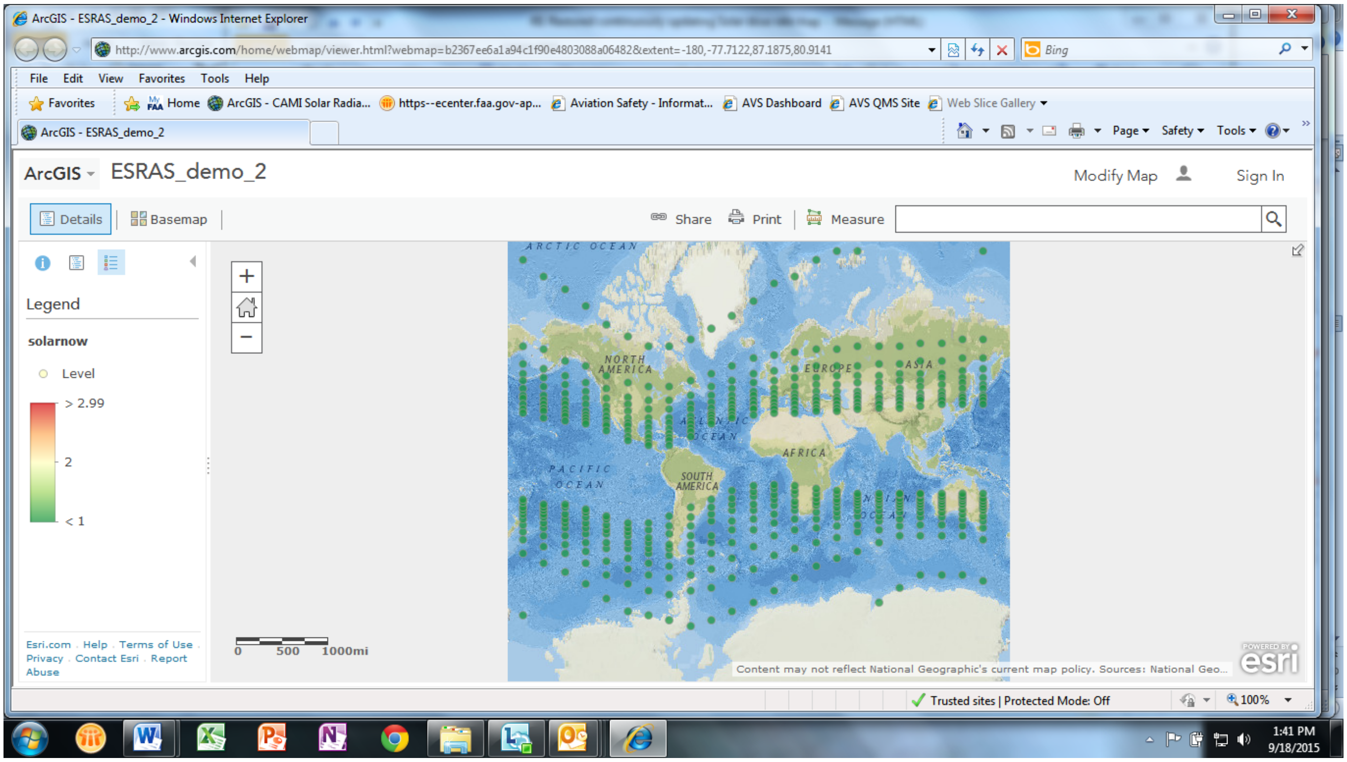

Figure 1. Solar radiation map for normal conditions. Red dots would indicate D_{700} = 3 or more, yellow would indicates D_{700} = 2, while green indicates D_{700} < 2.

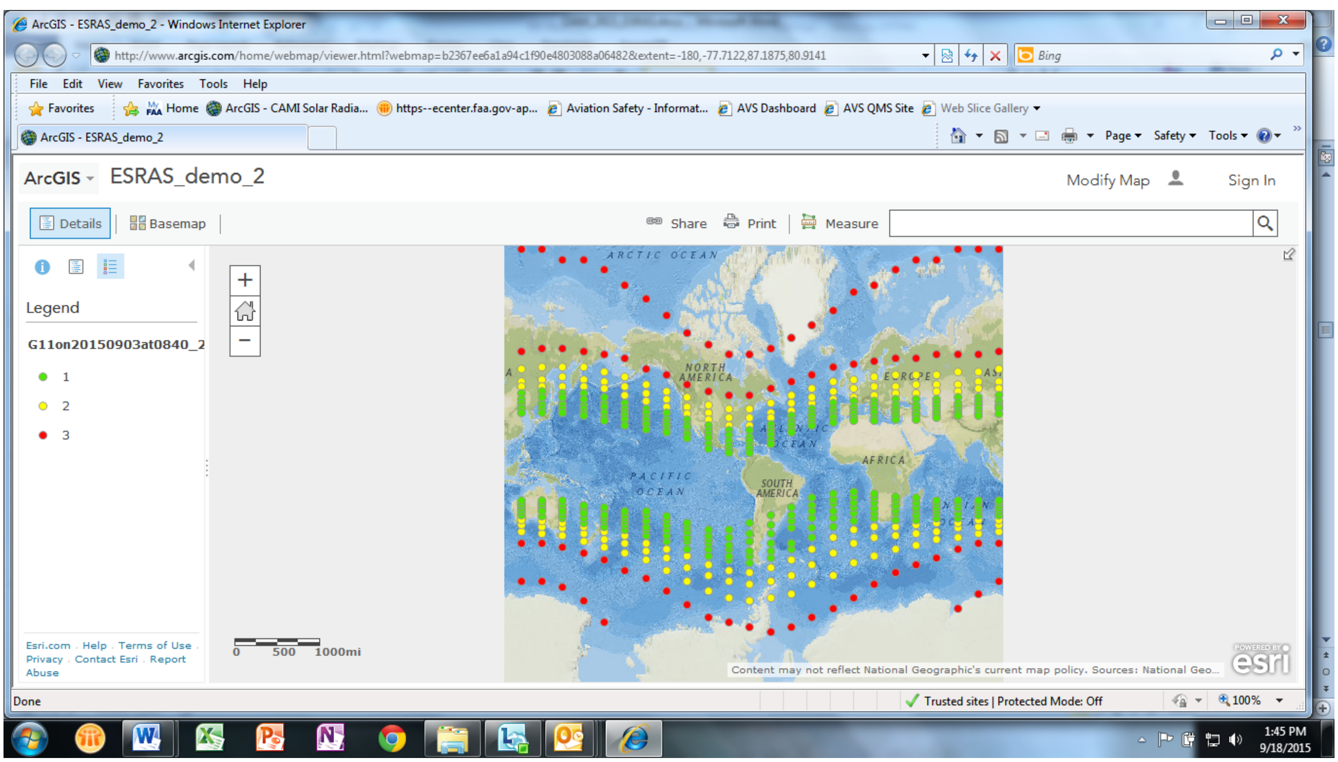

Figure 2. Solar radiation map mockup for conditions during a large solar proton event. Red dots indicate D_{700} = 3 or more, yellow indicates D_{700} = 2, and green indicates D_{700} < 2.

3. FUTURE FEATURES

The planned future enhancements to calculations include: the addition of solar alpha particle flux to the dose calculations, corrections for geomagnetic disturbance effects on global dose rates, and corrections for anisotropy based on available neutron monitor data. Other improvements that can be expected in the next few years include publishing global maps to the Internet at a permanent address and, as the older GOES satellites are phased out, a revision of the GOES proton spectrum evaluation algorithm to match the new GOES-N satellite series data, which are planned to be different in binning and energy range from previous GOES proton flux measurement instruments. The next generation map will likely be expanded to multiple layers, with each layer presenting the data at a different altitude, using color coded polygons, to further ease intuitive understanding of the dose rate data being presented.

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APPENDIX A

Glossary of radiation related terms

Absorbed Dose: The amount of energy absorbed by a medium divided by the mass of the medium. It is a macroscopic dose quantity. The medium could be the human body, a particular tissue or organ in the body, or some other object such as some part of a solid-state electronic device. The SI unit is the gray (Gy), where 1 Gy = 1 joule per kilogram (J/kg).

Ambient Dose Equivalent: Ambient dose equivalent is defined by the International Commission on Radiation Measurements and Units (ICRU) and the International Commission on Radiological Protection (ICRP) [ICRP, 1997] as the *dose equivalent* measured within a 30-cm diameter sphere of tissue equivalent material irradiated by a plane parallel beam. Doses at various depths, *d*, along the axis of the sphere opposing the incident radiation beam depth are denoted by $H^*(d)$. It is measured in units of joule per kilogram with the special name sievert (Sv). Because instruments can be calibrated to measure it, in aviation it is used as a surrogate measure of *effective dose*.

D index: A dose rate assessment index first suggested by Meier and Matthia [2014]. The D index ranks dose rate by powers of 2, normalized to 5 microsieverts per hour at D = 1, i.e.,

$$D = \log_2 (E/5) \tag{A1}$$

Dose Equivalent: ICRU and ICRP [ICRP, 1991] define dose equivalent (H) as the product of the *absorbed dose* and the *quality factor* (Q), i.e.,

$$H = D \cdot Q \tag{A2}$$

The value of Q is specified by the ICRP as relating to the unrestricted *linear energy transfer*, L_∞ of the radiation depositing the dose. The current recommended relationship is:

L_∞/ keV· μm^{-1}	$Q(L_\infty)$
<10	1
10-100	$0.32\, L_\infty - 2.2$
>100	$300\, (L_\infty)^{-1/2}$

Dose equivalent is measured in units of joule per kilogram with the special name sievert (Sv).

Effective Dose: Effective dose, E, was introduced as a radiation protection quantity by the ICRP in their 1990 recommendations [ICRP, 1991]. The U.S. National Council on Radiation Protection and Measurements (NCRP) published a slightly different definition in its Report 116 [NCRP, 1993]. Most recently, the ICRP currently defines effective dose as a weighted average of the sex-averaged organ equivalent doses to several different radiation-sensitive organs and tissues [ICRP, 2007]:

$$E = \sum_T w_T H_T = \sum_T w_T \left(\sum_R w_R D_{T,R} \right) \tag{A3}$$

The tissue weighting factors, w_T (Table A1), take into account the sensitivity of the various organs and tissues to radiation induced stochastic effects while the radiation weighting factors, w_R (Table A2), account for the relative biological effectiveness of each of the various radiations incident on the body. The anthropomorphic phantoms to be used in the calculations are now specified and are defined in ICRP Publication 110 [ICRP, 2009]. It is measured in units of joule per kilogram with the special name sievert (Sv). Dose limits are often expressed in effective dose.

Effective Vertical Cutoff Rigidity: There is a region above the minimum *vertical cutoff rigidity* where not all rigidities allow access. The effective vertical cutoff rigidity is a single value used to represent the effect of this region on particle access. It is usually slightly greater than the minimum vertical cutoff rigidity. Ideally, it is chosen such that calculations using the entering particle spectrum and treating the effective vertical cutoff rigidity as a sharp cutoff yield the same results as the physical measurements of the system, such as neutron monitor count rates, aircrew doses, etc.

Galactic Cosmic Radiation: Radiation from outside our solar system.

Geopotential Altitude: Altitude system based on height above mean sea level adjusted for gravity. In a standard atmosphere with an assumed, fixed temperature profile, pressure is constant with respect to geopotential altitude. Altitudes differ from geometric altitude by less than 1 percent below a few hundred thousand feet.

Gray: The gray (Gy) is the International System (SI) unit of *absorbed dose* of ionizing radiation. One Gy is 1 joule (J) of radiation energy absorbed per kilogram (kg) of matter.

Heavy ion: Traditionally, an ion in the galactic cosmic ray flux that is an atom of element 3 or higher (i.e., lithium and heavier) that has been stripped of all its electrons. It is also referred to as an *HZE* (high *Z* [atomic number] and *E* [energy]) particle. Sometimes the term can include any stripped nucleus with more than one nucleon. Astrophysicists and astronomers also call these *metals*.

HZE: See *heavy ion* entry.

Ionizing Radiation: Radiation that is sufficiently energetic to directly or indirectly eject an orbital electron from an atom.

ICRU Sphere: An ICRU-defined *phantom*. It consists of a 30-cm diameter tissue-equivalent sphere.

Isotropic: Equal from all directions.

Linear Energy Transfer (LET): Linear energy transfer is the average amount of energy per unit track length imparted to a medium by ionizing radiation of a specified energy, when penetrating a short distance. The energy imparted to the medium includes energy from any secondary radiation, such as nuclear particles released from a nucleus impacted by a high-energy neutron. LET is usually expressed in units of $\text{keV}\bullet\mu\text{m}^{-1}$ (thousand electron volts per micrometer). A radiation with an LET $<10\ \text{keV}\bullet\mu\text{m}^{-1}$ is generally considered low-LET. Photons, muons, electrons, and positrons are almost always low-LET. A radiation with an LET $>50\ \text{keV}\bullet\mu\text{m}^{-1}$ is generally considered high-LET. Neutrons, pions, and alpha particles are examples of radiations that are most often high-LET. Except near the end of its track, a proton is low-LET. However, protons are more damaging than other low-LET radiations (Hada and Sutherland, 2006). Thus, when risk estimates are calculated, protons are sometimes grouped with high-LET radiation.

Metals: See *heavy ion* entry.

Organ equivalent dose: The organ equivalent dose (also called *equivalent dose*), H, to a tissue or organ T from radiation R is defined as:

$$H_{T,R} = w_R D_{T,R} \qquad \text{(A4)}$$

where, w_R is the radiation weighting factor for radiation R (Table A.1) [ICRP, 1991; 2007], and $D_{T,R}$ is the absorbed dose to tissue or organ T from radiation R. The values of w_R are based on the *relative biological effectiveness* (RBE) for *stochastic effects*. For each type of primary radiation from outside the body (or internal emitter), the radiation weighting factor takes into account the effectiveness of the primary radiation and all its secondary radiations. For multiple radiations, H_T, the total organ equivalent dose to tissue or organ T is the sum of the organ equivalent doses from each type of radiation:

$$H_T = \sum_R H_{T,R} \qquad \text{(A5)}$$

Particle spectrum: The distribution of particle fluence or flux, usually with respect to particle energy, particle energy per nucleon, or particle rigidity.

Primary Radiation: In this context, radiation that reaches the top of Earth's atmosphere (See also *secondary radiation*).

Percent Deviation: An indication of the degree of variation of one quantity, "A" relative to another, "B".

$$\text{Percent deviation} = 100\ (A\text{-}B)/B \tag{A6}$$

Phantom: A target defined for performing calculations of dose in simulated exposures to ionizing radiation. It may be simple, like the *ICRU sphere* (a sphere of solid homogeneous tissue), or it may very complex, such as those defined in ICRP Publication 110 (derived from whole-body CT scans) [ICRP, 2009].

Rigidity: Momentum per unit charge. Rigidity (*R*) is used in cosmic ray propagation problems because particles of the same rigidity all follow the same path through a magnetic field.

Relative Biological Effectiveness: Relative biological effectiveness (RBE) is the ratio of *absorbed dose* of a reference radiation (e.g., gamma radiation from the decay of cobalt-60) to absorbed dose of the radiation in question, in producing the same magnitude of the same effect in a particular experimental organism or tissue. The RBE is influenced by the biological endpoint and the *LET* of the radiation. For example, the RBE for killing human cells increases with an increase in LET to about 100 keV•μm^{-1} and then decreases with further increase in LET. At LET 100 keV•μm^{-1}, the average separation between ionizing events is close to the diameter of the DNA double helix (a few μm). Therefore, a radiation with LET 100 keV•μm^{-1} can most efficiently produce a double-strand break in a DNA molecule by a single LET track [Hall and Giaccia, 2006]. Double-strand breaks in DNA molecules are thought to be the main cause of DNA related biological effects, because they are more difficult to properly repair than are single strand breaks.

Secondary Radiation: Particles or photons produced by the interaction of primary radiation with matter (see also *primary radiation*).

Sievert: Sievert (Sv) is the SI unit of *organ equivalent dose*, *ambient dose equivalent*, and *effective dose*. It quantifies harm from *stochastic effects*.

Solar Cosmic Radiation: Ionizing radiation from the Sun.

Solar Cycle: While the Sun has several cycles, in this context it refers specifically to the approximately 11-year cycle of change of polarity of the Sun's magnetic field. This both modulates *galactic cosmic radiation* and the occurrence of *solar proton events*.

Solar Proton Event: Event defined by NOAA as 3 or consecutive 5-minute periods with flux of 10 pfu of solar protons with energies at or above 10 MeV.

Solar Radiation: See *solar cosmic radiation.*

Stochastic Effect: Radiation effect for which the chance of incidence, but not the severity, is related to the dose (e.g., cancer).

Vertical Cutoff Rigidity: The *rigidity* a particle must have to approach a location from the vertical direction. It is often used as an indicator of the effectiveness of the Earth's magnetic field at deflecting energetic ions arriving from outer space.

Table A.1. ICRP [1991; 2007] recommended values for tissue weighting factors (w_T).

Pub. 60		Pub. 103	
Tissue	**Tissue Weight Factor**	**Tissue**	**Tissue Weight Factor**
Gonads	0.20	Bone marrow (red)	0.12
Bone marrow (red)	0.12	Colon	0.12
Colon	0.12	Lung	0.12
Lung	0.12	Stomach	0.12
Stomach	0.12	Breast	0.12
Bladder	0.05	Remainder tissues [B]	0.12
Breast	0.05	Gonads	0.08
Liver	0.05	Bladder	0.04
Oesophagus	0.05	Oesophagus	0.04
Thyroid	0.05	Thyroid	0.04
Skin	0.01	Liver	0.04
Bone surface	0.01	Bone surface	0.01
Remainder tissues [A]	0.05	Skin	0.01
		Brain	0.01
		Salivary glands	0.01

[A] Adrenals, brain, upper large intestine small intestine, kidneys, muscle, pancreas, spleen, thymus and uterus.
[B] Adrenals, extra-thoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus and uterus/cervix.

Table A.2. Recommended values for radiation weighting factors (w_R).[a]

Type and energy of the radiation		w_R	
		ICRP (2007)	
Photons, electrons, muons		1	
Protons, charged pions		2	
Alpha particles, fission fragments, heavy ions		20	
Neutrons	(energy, E_n)		
	E_n <1 MeV	$2.5 + 18.2 \times \exp[-(\ln(E_n))^2 / 6]$	
	E_n 1 MeV to 50 MeV	$5.0 + 17.0 \times \exp[-(\ln(2E_n))^2 / 6]$	
	E_n >50 MeV	$2.5 + 3.25 \times \exp[-(\ln(0.04E_n))^2 / 6]$	
		NCRP (1993)	ICRP (1991)
Photons, electrons, muons		1	1
Protons [b]		2 [c]	5
Alpha particles, fission fragments, heavy ions		20	20
Neutrons	(energy, E_n)		
	E_n <10 keV	5	5
	E_n 10 keV to 100 keV	10	10
	E_n >100 keV to 2 MeV	20	20
	E_n >2 MeV to 20 MeV	10	10
	E_n >20 MeV	5	5

[a] For radiations not in the table, both ICRP and NCRP recommend using the mean quality factor, rounded up to the nearest whole number.
[b] Except recoil protons, E_p >2 MeV.
[c] If E_p >100 MeV, NCRP suggests w_R=1 is more appropriate.

APPENDIX B

Data Availability

Due to the large size of the tables, the following data are made available electronically:

- Atmospheric response tables to convert primary particle fluence to effective dose at altitude for protons and alpha particles.
- A 1 by 1 degree world grid of effective vertical cutoff rigidities at 20 km.

Please send e-mail requests and inquiries to:
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