48th International Conference on Environmental Systems
8-12 July 2018, Albuquerque, New Mexico
ICES-2018-240

# Estimates of Radiation Exposures to Crews on Missions in Cis-Lunar Space from the October 1989 Series of Solar Particle Events

Lawrence W. Townsend[1], Wouter C. de Wet.[2], and Fahad Zaman[3]
*The University of Tennessee, Knoxville, Tennessee,37996-2300*

**In its 2008 report, the National Research Council recommended against the use of the King spectrum August 1972 solar energetic particle event as the design standard. It was stated in the Council report that radiation exposures from other events in the historical record could exceed those from the 1972 event. Instead, the Council recommended that other events, such as the October 1989 event, be used in place of the 1972 event. In this work we present estimates of radiation exposures to male and female crew members in cis-lunar space from the summed spectrum of the October 1989 series of events and from the August 1972 King spectrum. These estimates are obtained for both aluminum and polyethylene shields, and compared to NASA short-term exposure limits.**

## Nomenclature

$\gamma_1, \gamma_2$ = spectral indices, unitless
*BFO* = blood forming organ\
*CAF* = Computerized Anatomical Female
*CAM* = Computerized Anatomical Man
*CNS* = central nervous system
*D* = absorbed dose
*MeV* = mega electron volt(s)
*NASA* = National Aeronautics and Space Administration
*OLTARIS* = Online Tool for the Assessment of Radiation Effects in Space
*R* = proton rigidity (momentum per unit charge), megavolts
$R_0$ = characteristic rigidity, megavolts
*RBE* = Relative Biological Effectiveness
*REID* = risk of exposure induced death
*SPE* = solar particle event

## I. Introduction

THE radiation environment in cis-lunar space presents hazards to spcefaring crews from two main sources: the ever-present galactic cosmic ray environment and sporadic solar particle events. Historically, NASA has used the King spectrum representation of the incident proton spectrum as its design basis event[1]. Although this event has one of the largest proton fluences, its energy spectrm is fairly soft (decreases rapidly with increasing proton energy). As a result, the event presents a radiation hazard to crews in spacesuits or thinly-shielded spacecraft, but is relatively easy to shield with moderate levels of shielding.[2,3]. Initial studies of the October 1989 events[2,3] used preliminary spectra obtained from an unnumbered, unpublished NOAA SEC report. The doses and dose equivalents estimated for the 1989 events were comparable to the August 1972 values. These analyses, however, used an exponential in rigidity (momentum per unit charge) spectrum representation for the events that incorrectly extrapolated them to proton energies above 100 MeV In 2010, Atwell and collaborators published dose estimates for both the 1972 and 1989 events utilizing a Band function fit, which properly represents the high energy ( > 100 MeV) proton spectrum[4]. As a result, the October 1989 event exposures were larger than those from the August 1972 event since its spectrum

---

[1] Chancellor's Professor Emeritus, Department of Nuclear Engineering.
[2] Graduate Research Assistant, Department of Nuclear Engineering.
[3] Graduate Research Assistant, Department of Nuclear Engineering.

was harder at high energies than the 1972 event. However, the Band function parameters were not published in archival literature, but were made available to the research communication by private communication from Tylka.

In a 2008 report, the National Research Council recommended that NASA discontinue use of the August 1972 King spectrum as its design standard since exposures from that event could be exceeded by exposures from more recent events for exploration-type missions. Instead, the recommendation was made to consider the 0ctober 1989 series of events as an alternative[5]. More recently, a group of experts at an SPE Technical Interchange Meeting at NASA Langley formally recommended that NASA adopt the summed spectrum from the October 19-24, 1989, series of events as the design standard spectrum for use in estimating radiation protection requirements for future cis-lunar missions[6]. That paper, for the first time, published the Band function fits for the October 1989 series of events in the open, archival literature. In this work, we utilize these published spectra to re-examine the expected exposures to both male and female crew members from the October 1989 event series and compare them to the expected exposures from the August 1972 King spectrum behind both aluminum and polyethylene shielding.

## II. Computational Methods

We assume that crewmembers (male and female) are located within a spherical, spacecraft shell shielding having areal densities ranging from 0.1 to 20 g cm$^{-2}$. Shield compositions are assumed to be either aluminum or polyethylene. The incident rsdiation spectrum is assumed to be either the King spectrum representation of the August 1972 SPE[7], or the summed spectrum for the October 19-24, 1989 SPEs[6], as originally modeled by Tylka using the Band function parameterization. The August 1972 proton spectrum, as presented in Ref. 7, is given by

$$J(>E) = J_0 \exp\left[\left(30-E\right)/26.5\right] \tag{1}$$

where J is the proton integral fluence (cm$^{-2}$) with energies greater than E, $J_0 = 7.9\times10^{9}$cm$^{-2}$, and E is proton energy in MeV. The October 1989 events are given by

$$\begin{aligned} J\left(>R\right) &= J_0 R^{-\gamma_1} \exp\left(-R/R_0\right);\ for\ R \le \left(\gamma_2-\gamma_1\right)R_0 \\ J\left(>R\right) &= J_0 R^{-\gamma_2} \left\{\left[\left(\gamma_2-\gamma_1\right)R_0\right]^{\left(\gamma_2-\gamma_1\right)} \exp\left(\gamma_2-\gamma_1\right)\right\};\ for\ R \ge \left(\gamma_2-\gamma_1\right)R_0 \end{aligned} \tag{2}$$

Where R is the proton rigidity (momentum per unit charge), J is the proton integral fluence with rigidities greater than R, and ($J_0$, $R_0$, $\gamma_1$, $\gamma_1$) are parameters whose values are displayed in Table 1 for the series of October events.

**Table 1. Otober 1989 event spectrum parameters**

| Event Date | $J_0$ (cm$^{-2}$) | $R_0$ (MV) | $\gamma_1$ | $\gamma_2$ |
|---|---|---|---|---|
| 10/19a/2018 | $1.22\times10^{9}$ | 162.1 | 0.528 | 5.81 |
| 10/19b/2018 | $9.09\times10^{9}$ | 84.35 | 0.911 | 4.43 |
| 10/22/2018 | $1.09\times10^{9}$ | 135.2 | 1.226 | 7.25 |
| 10/24/2018 | $4.42\times10^{7}$ | 385.0 | 2.176 | 5.65 |

These spectra are transported through the spherical space craft shielding and then through the human body, using the OLTARIS website at NASA Langley Research Center (https://oltaris.nasa.gov), to estimate effective doses and organ doses for the male and female crew members. The human geometry models used in the calculations are the Computerized Anatomical Male (CAM)[8] and Computerized Anatomical Female (CAF)[9] models. It is assumed that the space craft is located in cis-lunar space outside Earth's geomagnetic field. The NASA permissible radaition exposure limits[10] for critical body organs are shown in Table 2. For the eye lens, skin and blood forming organs (BFO), the units are in centiGray- equivalent (cGy-Eq) , which is calculated by multiplying the absorbed dose , D(cGy), by a unitless relative biological effectiness (RBE) factor to account for differences in biological damage effectiveness for protons over gammas and x-rays (reference radiations). For protons[11], RBE = 1.5. For the heart and central nervous system (brain), the RBE is unknown, so the limits are expressed directly in absorbed dose (cGy). Aside from the limts in Table 2, which are to prevent short-term and noncancer effects, there are also career effective dose limits, which are imposed to reduce the possibility of space radiation exposures to astronauts resulting in a fatal cancer. These are specific to the mission duration and the radiation environment the astronaut is expected to be exposed to. They are obtained by applying the criteria that the risk od exposure induced death (REID) is limited to 3% at the 95% confidence limit. Table 3 presents representative effective dose limits for exposures to SPEs during a one year mission. Note that they are both[12] age and sex-dependent.

**Table 2. NASA Permissible Exposure Limits for Critical Organs**

| Organ | 30 Day | 1 Year (cGy-Eq) | Career (cGy-Eq) |
|---|---|---|---|
| Lens | 100 cGy-Eq | 200 cGy-Eq | 400 cGy-Eq |
| Skin | 150 cGy-Eq | 300 cGy-Eq | 600 cGy-Eq |
| BFO | 25 cGy-Eq | 50 cGy-Eq | N/A |
| Heart | 25 cGy | 50 cGy | 100 cGy |
| CNS | 50 cGy | 100 cGy | 150 cGy |

**Table 3. NASA Career Permissible Exposure Limits for Solar Particle Events for a One Year Mission**

| Age (years) | Effective Dose (cSv) | |
|---|---|---|
| | Female | Male |
| 30 | 17.4 | 23.0 |
| 35 | 20.4 | 26.7 |
| 40 | 23.0 | 29.6 |
| 45 | 27.8 | 35.2 |
| 50 | 34.1 | 42.0 |

## III. Results

The computational results obtained from the OLTARIS website for the 1972 and 1989 events are presented in Tables 4 through 7 for female crew members and in Tables 8 through 11 for males.

### A. Female Crew Exposures

**Table 4. Organ dose and effective dose for female crew members for the summed October 1989 event spectrum shielded by aluminum. Values exceeding 30d short-term organ limits and career effective dose limits for 30y old females are in bold type.**

| Al Shield (g cm$^{-2}$) | Skin Dose (cGy-Eq.) | Eye Dose (cGy-Eq.) | BFO Dose (cGy-Eq.) | CNS Dose (cGy) | Heart Dose (cGy) | Effective Dose (cSv) |
|---|---|---|---|---|---|---|
| 0.1 | **13640** | **1180** | **150** | **72** | **61** | **553** |
| 0.4 | **3719** | **874** | **136** | **68** | **59** | **229** |
| 1 | **1346** | **562** | **114** | **62** | **55** | **144** |
| 5 | **176** | **142** | **57** | 38 | **38** | **59** |
| 10 | 71 | 66 | **34** | 24 | **26** | **37** |
| 20 | 28 | 28 | 18 | 22 | 16 | **23** |

In Table 4 note that all of the dose limts for females are exceeded for the thinnest shields (0.1 and 0.4 g cm$^{-2}$). For 1 g cm$^{-2}$ shielding all organ limits are exceeded. Behind 5 g cm$^{-2}$ only the brain (CNS) and effective dose values are below limits. Behind 10 g cm$^{-2}$ both the BFO and heart doses exceed limits. All organ dose values are below all limits behind 20 g cm$^{-2}$ Al shielding. In all cases shown, the effective dose limits are exceeded. Finally, if aluminum is the shield material, a storm shelter on the order of 20 g cm$^{-2}$ appears adequate to protect against short-term effects. However, the career effective dose limits will be exceeded for those female crew members under 40y of age.

**Table 5. Organ dose and effective dose for female crew members for the August 1972 event spectrum shielded by aluminum. Values exceeding 30d short-term organ limits and career effective dose limits for 30y old females are in bold type.**

| Al Shield (g cm$^{-2}$) | Skin Dose (cGy-Eq.) | Eye Dose (cGy-Eq.) | BFO Dose (cGy-Eq.) | CNS Dose (cGy) | Heart Dose (cGy) | Effective Dose (cSv) |
|---|---|---|---|---|---|---|
| 0.1 | **5940** | **1844** | **290** | **120** | **75** | **428** |
| 0.4 | **3696** | **1606** | **260** | **111** | **71** | **338** |
| 1 | **2169** | **1164** | **213** | **96** | **63** | **252** |
| 5 | **376** | **279** | **74** | 41 | **30** | **81** |
| 10 | 103 | 84 | **28** | 16 | 15 | **35** |
| 20 | 18 | 17 | 8 | 4 | 6 | 15 |

Table 5 presents results for female crew members shielded by aluminum from the August 1972 event. Note that all of the organ dose limts for females are exceeded for the thin shields (0.1, 0.4, and 1 g cm$^{-2}$). Behind 5 g cm$^{-2}$ only the brain (CNS) dose is below limits. Behind 10 g cm$^{-2}$ only the BFO dose exceeds limits. All organ dose values are below all limits behind 20 g cm$^{-2}$ Al shielding. In all cases shown, the effective dose limits are exceeded except for the thick, 20 g cm$^{-2}$ shield . Thus, if aluminum is the shield material, a storm shelter on the order of 20 g cm$^{-2}$ appears adequate to provide crew exposure protection. Comparing the organ dose and effective dose results in Tables 4 and 5 for the two events, it is clear that the organ doses are generally higher for the August 1972 event than for the October 1989 event series, except for the thicker shields, where the doses from the October 1989 series are more than 50% higher.

**Table 6. Organ dose and effective dose for female crew members for the summed October 1989 event spectrum shielded by polyethylene (PE). Values exceeding 30d short-term organ limits and career effective dose limits for 30y old females are in bold type.**

| PE Shield (g cm$^{-2}$) | Skin Dose (cGy-Eq.) | Eye Dose (cGy-Eq.) | BFO Dose (cGy-Eq.) | CNS Dose (cGy) | Heart Dose (cGy) | Effective Dose (cSv) |
|---|---|---|---|---|---|---|
| 0.1 | **9656** | **1126** | **148** | **71** | **61** | **412** |
| 0.4 | **2454** | **761** | **129** | **67** | **58** | **188** |
| 1 | **868** | **446** | **104** | **59** | **53** | **119** |
| 5 | 113 | 99 | **46** | 32 | **33** | **46** |
| 10 | 45 | 44 | **25.5** | 18 | 21 | **27** |
| 20 | 17 | 17 | 12 | 8 | 11 | 14 |

Table 6 presents results for female crew members shielded by polyethylene from the summed October 1989 seies of events. Overall, we note that polyethylene reduces organ dose and effective doses, compared to aluminum, by more than 20% fror all shield thicknesses. Again we note that all limits are exceded for shields 1 g cm$^{-2}$ and thinner. For shields 5 g cm$^{-2}$ thick, only BFO dose, Heart dose and effective dose exceed limits. Behind 10 g cm$^{-2}$ shielding, the effective dose limit is exceeded and the BFO limit is barely exceeded. All organ dose and effective dose values are below limits for a 20 g cm$^{-2}$ polyethylene shield.

Table 7 presents results for female crew members shielded by polyethylene from the August 1972 event. Note that all of the organ dose limts for females are exceeded for the thin shields (0.1, 0.4, and 1 g cm$^{-2}$). Behind 5 g cm$^{-2}$ the brain (CNS) and Heart doses are below limits. Behind 10 g cm$^{-2}$ all of the organ doses are below limits. All organ dose values are below all limits behind 20 g cm$^{-2}$ Al shielding. In all cases shown, the effective dose limits are exceeded except for the thick, 20 g cm$^{-2}$ shield. Thus, if polyethylene is the shield material, a storm shelter on the order of 20 g cm$^{-2}$ appears adequate to provide crew exposure protection. Comparing the organ dose and effective dose results in Tables 6 and 7 for the two events, it is clear that the organ doses are generally higher for the August 1972 event than for the October 1989 event series, except for the thicker shields, where the doses from the October 1989 series are lower.

**Table 7. Organ dose and effective dose for female crew members for the August 1972 event spectrum shielded by aluminum. Values exceeding 30d short-term organ limits and career effective dose limits for 30y old females are in bold type.**

| Al Shield (g cm$^{-2}$) | Skin Dose (cGy-Eq.) | Eye Dose (cGy-Eq.) | BFO Dose (cGy-Eq.) | CNS Dose (cGy) | Heart Dose (cGy) | Effective Dose (cSv) |
|---|---|---|---|---|---|---|
| 0.1 | **5314** | **1890** | **286** | **119** | **75** | **406** |
| 0.4 | **3023** | **1460** | **247** | **107** | **69** | **306** |
| 1 | **1625** | **964** | **188** | **88** | **58** | **213** |
| 5 | **212** | **168** | **49** | 28 | 22 | **53** |
| 10 | 46 | 40 | 15 | 9 | 9 | **19** |
| 20 | 6 | 6 | 4 | 2 | 3 | 7 |

### B. Male Crew Exposures

**Table 8. Organ dose and effective dose for male crew members for the summed October 1989 event spectrum shielded by aluminum. Values exceeding 30d short-term organ limits and career effective dose limits for 30y old males are in bold type.**

| Al Shield (g cm$^{-2}$) | Skin Dose (cGy-Eq.) | Eye Dose (cGy-Eq.) | BFO Dose (cGy-Eq.) | CNS Dose (cGy) | Heart Dose (cGy) | Effective Dose (cSv) |
|---|---|---|---|---|---|---|
| 0.1 | **13780** | **1159** | **136** | **73** | **58** | **600** |
| 0.4 | **3775** | **856** | **123** | **60** | **56** | **267** |
| 1 | **1369** | **550** | **105** | **55** | **53** | **171** |
| 5 | **177** | **139** | **54** | 35 | **36** | **64** |
| 10 | 71 | 64 | **33** | 22 | **25** | **39** |
| 20 | 28 | 28 | 18 | 12 | 15 | **23** |

In Table 8 note that all of the dose limts for males are exceeded for the thinnest shields (at or below 1g cm$^{-2}$). Behind 5 g cm$^{-2}$ only the brain (CNS) is below the limit. Behind 10 g cm$^{-2}$ the BFO exceeds the limit and the heart dose is at the limit. All organ dose values are below all limits behind 20 g cm$^{-2}$ Al shielding. In all cases shown, the effective dose limits are exceeded above 30y of age, except that the limit is not exceeded for males 50y of age.. For 30y old males, the effective dose is at the limit. Finally, if aluminum is the shield material, a storm shelter on the order of 20 g cm$^{-2}$ appears adequate to protect against short-term effects.

Table 9 presents results for male crew members shielded by aluminum from the August 1972 event. Note that all of the organ dose limts for males are exceeded for the thin shields (0.1, 0.4, and 1 g cm$^{-2}$). Behind 5 g cm$^{-2}$ only the brain (CNS) dose is below limits. Behind 10 g cm$^{-2}$ only the BFO dose exceeds limits. All organ dose values are below all limits behind 20 g cm$^{-2}$ Al shielding. In all cases shown, the effective dose limits are exceeded except for the thick, 20 g cm$^{-2}$ shield . Thus, if aluminum is the shield material, a storm shelter on the order of 20 g cm$^{-2}$ appears adequate to provide crew exposure protection. Comparing the organ dose and effective dose results in Tables 8 and 9 for the two events, it is clear that the organ doses are generally higher for the August 1972 event than for the October 1989 event series, except for the thicker shields, where the doses from the October 1989 series are more than 50% higher.

**Table 9. Organ dose and effective dose for male crew members for the August 1972 event spectrum shielded by aluminum. Values exceeding 30d short-term organ limits and career effective dose limits for 30y old males are in bold type.**

| Al Shield (g cm$^{-2}$) | Skin Dose (cGy-Eq.) | Eye Dose (cGy-Eq.) | BFO Dose (cGy-Eq.) | CNS Dose (cGy) | Heart Dose (cGy) | Effective Dose (cSv) |
|---|---|---|---|---|---|---|
| 0.1 | **6037** | **1901** | **260** | **99** | **71** | **535** |
| 0.4 | **3761** | **1569** | **234** | **92** | **67** | **420** |
| 1 | **2208** | **1136** | **192** | **80** | **59** | **320** |
| 5 | **384** | **273** | **68** | 35 | **29** | **96** |
| 10 | 104 | 82 | **26** | 14 | 14 | **39** |
| 20 | 18 | 17 | 8 | 4 | 6 | 16 |

**Table 10. Organ dose and effective dose for male crew members for the summed October 1989 event spectrum shielded by polyethylene (PE). Values exceeding 30d short-term organ limits and career effective dose limits for 30y old females are in bold type.**

| PE Shield (g cm$^{-2}$) | Skin Dose (cGy-Eq.) | Eye Dose (cGy-Eq.) | BFO Dose (cGy-Eq.) | CNS Dose (cGy) | Heart Dose (cGy) | Effective Dose (cSv) |
|---|---|---|---|---|---|---|
| 0.1 | **9769** | **1105** | **134** | **63** | **58** | **456** |
| 0.4 | **2494** | **745** | **118** | **59** | **55** | **223** |
| 1 | **882** | **436** | **96** | **53** | **51** | **143** |
| 5 | 114 | 97 | **43** | 29 | **31** | **49** |
| 10 | 46 | 43 | 24 | 17 | 20 | **27** |
| 20 | 17 | 17 | 12 | 8 | 10 | 14 |

Table 10 presents results for male crew members shielded by polyethylene from the summed October 1989 series of events. Overall, we note that polyethylene reduces organ dose and effective doses, compared to aluminum, by more than 20% fror all shield thicknesses. Again we note that all limits are exceded for shields 1 g cm$^{-2}$ and thinner. For shields 5 g cm$^{-2}$ thick, only BFO dose, Heart dose and effective dose exceed limits. Behind 10 g cm$^{-2}$ shielding, only the effective dose limit is exceeded. All organ dose and effective dose values are below limits for a 20 g cm$^{-2}$ polyethylene shield.

**Table 11. Organ dose and effective dose for male crew members for the August 1972 event spectrum shielded by polyethylene (PE). Values exceeding 30d short-term organ limits and career effective dose limits for 30y old males are in bold type.**

| PE Shield (g cm$^{-2}$) | Skin Dose (cGy-Eq.) | Eye Dose (cGy-Eq.) | BFO Dose (cGy-Eq.) | CNS Dose (cGy) | Heart Dose (cGy) | Effective Dose (cSv) |
|---|---|---|---|---|---|---|
| 0.1 | **5403** | **1890** | **286** | **119** | **75** | **511** |
| 0.4 | **3078** | **1460** | **247** | **107** | **69** | **391** |
| 1 | **1653** | **964** | **188** | **88** | **58** | **271** |
| 5 | **215** | **168** | **49** | 28 | 22 | **61** |
| 10 | 46 | 40 | 15 | 9 | 9 | 20 |
| 20 | 6 | 6 | 4 | 2 | 3 | 7 |

Table 11 presents results for male crew members shielded by polyethylene from the August 1972 event. Overall, we note that polyethylene reduces organ dose and effective doses, compared to aluminum, by more than 20% fror all shield thicknesses. Again we note that all limits are exceded for shields 1 g cm$^{-2}$ and thinner. For shields 5 g cm$^{-2}$ thick, skin, eye, BFO, and effective dose exceed limits. For 10 g cm$^{-2}$ shielding and greater, all organ dose and effective dose values are below limits.

## IV. Conclusions

Estimates of critical organ dose and effective doses for male and female crew members in cis-lunar space shielded by alumninum and polyethylene shielding, ranging from 0.1 g cm$^{-2}$ to 20 g cm$^{-2}$ in areal density, were made for exposures for the current NASA design standard solarparticle event (August 1972), and a recently-proposed revised standard using the summed spectra for the solar particle events of October 19, 22, and 24. Comparing the organ doses for the two standards, the organ doses and effective doses were generally larger for the August 1972 event for thinner shields (~ 5 g cm$^{-2}$) of both materials, and larger for the October 1989 series for shields ~ 20 g cm$^{-2}$ thickness. Thus, for exploration missions, the use of the 1972 event as a standard is likely to underestimate doses for events with hard energy spectra, similar to those in the Octobert 1989 series, especially if there are severe constraints on the mass of spacecraft structure and shielding. As expected, organ doses were generally lower for males than for females due to the larger body mass for males. However, these differences became negligible for internal organs inside spacecraft with shielding thicknesses ~ 20 g cm$^{-2}$. We also note that organ doses, except for skin, are lower for polyethylene shielding than aluminum due to its lower atomic mass constuents and hydrogen content. Finally, even for thicker shields, effective doses from an SPE can sometimes exceed NASA guidelines when critical organ doses are below the short-term limits.

## Acknowledgments

Useful information exchanges with Chris Sandridge at NASA Langley Research Center concerning uploading shielding files to the OLTARIS website are gratefully acknowledged.

## References

[1]"NASA Human Integration Design Handbook", NASA Special Publication SP-2010-3407, Rev A., Washington, DC, 2010.

[2]Townsend, L.W., Nealy, J.E., Wilson, J.W., and Atwell, W.,"Large Solar Flare Radiation Shielding Requirements for Manned Interplanetary Missions," *Journal of Spacecraft and Rockets.* Vol. 26, No. 2, 1989, pp. 126-128.

[3]Townsend, L.W., Cucinotta, F.A., Shinn, J.L., and Wilson, J.W., "Risk Analyses for the Solar Particle Events of August through December 1989," *Radiation Research*, Vol. 130, No. 1. 1992, pp. 1-6.

[4]Atwell, W., Tylka, A., Dietrich, W., and Rojdev, K., "Band Function Fit to 23rd Solar Cycle Grounfd Level Proton Events and radiation Exposure Estimates," *40th International Conference on Environmental Systems*, 2010, Paper No. AIAA 2010-6187.

[5]National Research Council, "Managing Space Radiation Risk in the New Era of Space Exploration," 2008, Washington, DC: The National Academies Press. https://doi.org/10.17226/12045.

[6]Townsend, L.W., Adams, J.H., Blattnig, S.R., Clowdsley, M.S, Fry, D.J., et al, "Solar Particle Event Storm Shelter Requirements for Missions Beyond Low Earth Orbit," *Life Sciences in Space Research*, 2018 (available online) https://doi.org/10.1016/j.lssr.2018.02.002

[7]King, J.H., "SolarProton Fluences for 1977-1983 Space Missions," *Journal of Spacecraft*, Vol. 11, No. 6, 1974, pp. 401-408.

[8] Billings, M.P., Yucker, W.R., "The Computerized Anatomical Man (CAM) Model," Summary Final Report, MDC-G4655, McDonnell Douglas Company, 1973.

[9] Yucker,W.R., Huston, S.L., "The Computerized Anatomical Female," Final Report MDC-6107, McDonnell Douglas Company, 1990.

[10] NASA (2007). *NASA Space Flight Human System Standard. Volume 1: Crew Health*, NASA-STD-3001.

[11]NCRP, "Radiation Protection Guidance for Activities in Low-Earth Orbit," National Council on Radiation Protection and Measurements, Report 132, Bethesda, MD, 2000.

[12] NASA (2014). "Human Integration Design Handbook (HIDH)," NASA/SP-2010-3407/REV1, June 5, 2014