Skoltech
Skolkovo Institute of Science and Technology

Thesis Changes Log

Name of Candidate: Mikhail Dobynde

PhD Program: Materials Science and Engineering

Title of Thesis: Radiation Shielding Of Astronauts During Interplanetary Flights

Supervisor: Prof. Rupert Gerzer

Chair of PhD defense Jury: Prof. Clement Fortin ***Email**: C.Fortin@skoltech.ru*

Date of Thesis Defense: 17 February 2020

The thesis document includes the following changes in answer to the external review process.

Reply to Prof. Panasyuk

Author appreciates Prof. Panasyuk for his agreement to review the thesis, for reading the manuscript and for his criticism.

My main comment comes down to the author's conclusion regarding the assessment of radiation hazard during a human flight to Mars: "The optimal time for flight to Mars is during the period of solar maximum in the decay phase and the optimal aluminum shielding thickness is 30 g * cm2. These parameters allow about 5.5 years of interplanetary flight duration before reaching the astronauts' career dose limit of 1 Sv". This assessment of the author is based on the SEP model in which extreme powerful solar events are considered as a basis of further calculations. However, there is another approach –probabilistic -to describing sporadic SEP events. The author mentions this model ("Probability SEP model of MSU, by Nymmik), but did not analyze the conclusions that follow from this model in comparison with his estimations of radiation doses. Nevertheless, the "Probabilistic model" leads to more pessimistic estimates (much less than 5.5 years) of the duration of a safe mission to Mars, noted by the author. Moreover, the latest direct measurements of the annual radiation dose give values of 0.6 -0.9 SV under the protection of more than 10 g / cm2 (almost in the absence of SCL events), which is comparable to the career dose limit. I would like to know the author's opinion on this matter.

Thank you for pointing this out. The reference to the “Probability SEP model” has been added to the review. Kuznetsov et al., 2012, used the “probability” model to estimate radiation doses in the Moon mission. The comparison between the paper and current results shows that radiation doses due to the GCR are in relatively good agreement, taking into account differences in geometry, irradiation conditions, energy grid for incident particles, the material of the phantom, dose calculation methodology and dose quantities. The agreement is found both for the total dose and dose due to the secondary neutrons. However, the radiation dose due to SEP, according to Kuznetsov et al., 2012 are much higher than in the current work. I see three main reasons. The first is that the SEP in the current work has been considered in the energy range up to 1 GeV/ nucleon, while Kuznetsov et al., 2012 considered energies up to 10 GeV/nucleon. The second reason can be due to the differences in the energy grid. In the current work, the energy range of primary particles is from 7 to 123 GeV/nucleon, although for the SEP, only the first 11 energy bins are used. Kuznetsov et al., 2012 use five energy bins and do not specify the boundary values for bins as well as the energy distribution of primary particles in each bin. The related publication by Denisov et al., 2011, and Ph.D. thesis by Denisov also do not answer. The third possible reason is the very high flux prediction given by the "probability" SEP model. The possibility of exceeding the model spectrum is just 1%. Summing up, additional work should be done to give the exact answer to this question.

In addition, there are less significant comments. There are some points just to correct.

p.18. There are several models that describe GCR spectra: Nymmikmodel (Nymmik et al., 1992)

Corrected, thank you.

p.21. fluxes over South America and western part of Atlantic Ocean(the region on the South Atlantic anomaly)

Thank you for pointing this out, it is added to the description now.

p.20. Their spectra decrease exponentially and are usually described up to the energy of 10 MeV for electrons and up to 500 MeV (up to 1000 MeV) for protons

Corrected, thank you.

p. 28. Different SEP events have different risk levels for space missions, because of the differences in particle spectra. Hu et al., 2009 have shown that no single event would lead to acute radiation death if the aluminum spacecraft shielding exceeds 5 g·cm2. Thus, most risk due to SEPs is associated with extra vehicular activity (EVA). See my main comment above. It is not correct.

It has been corrected to "no single event among considered" followed the discussion about Kuznetsov et al., 2012.

p.29.LITERATURE REVIEW Absence of references to Sobolevsky's et al papers, which could be important for further development of this topic. Recommend to add.

The most relevant works of Prof. Sobolevsky have been added to the literature review, thank you for the suggestion.

p. 31.Several studies consider radiation doses during 500 and 1000-day flights according to NASA plans26 (what does it means?)

Sorry for confusing, the corresponding references have been added.

Reply to Prof. Ploc

Author appreciates Prof. Ploc for his agreement to review the thesis, for reading the manuscript and for his criticism.

To your abstract, add please a sentence or a paragraph explaining why you focus on calculations of radiation shielding to Mars only while the title is about the interplanetary missions in general. It would increase the relevance of the topic of dissertation work to its actual content.

The primary motivation at the beginning of the work was the assessment of radiation exposure during the flight to Mars, which is an interplanetary flight. We aimed to make a general assessment and demonstrated the optimal flight conditions, which are required for principal mission planning. Thus, we did not consider a specific trajectory and spacecraft geometry, which should be specified in the latter stages. Thus, the results of section 4.1, as well as 4.2, 4.3, and 4.5 can be used for any other interplanetary mission, like flight to Moon or interplanetary space station.

Neutrons have no charge, it is true, but the quality factor is not 1 as you stated in the thesis (section 1.2, page 8). Correct it and explain why. (See e.g. Veinot, K. G., & Hertel, N. E. (2005). Effective quality factors for neutrons based on the revised ICRP/ICRU recommendations. Radiation protection dosimetry, 115(1-4), 536-541.)

Thank you for pointing this out, the statement about the neutron quality factor equal to one has been removed. However, by a quality factor, we mean Q(LET), which is applied to the energy, which is deposited by particle itself, not for the associated secondary particles. If all radiation doses weighted by Q(LET) were attributed to initial neutron, the effective quality factor would be greater than one for sure.

Misprints, grammar errors, wrong spelling, and other editorial comments:

o Abstract:

§ First sentence: wrong: "...as a one on the main..."correct:"...as one of the main..."

Corrected, thank you.

§ Fourth line: use "trapped radiation (TR)" instead of "radiation trapped (TR)"

Corrected, thank you.

§ In the paragraph describing the second main outcome, second line: use "Circulatory System (CS)" instead of "Circulatory System (CSs)" in your text

Corrected, thank you.

§ In the paragraph describing the second main outcome, second line: up to 90% ("to" is missing in your text)

Corrected, thank you.

§ In the paragraph describing the third main outcome, last line: use more common and correct "the net CS dose on the LEO is halved" instead of "the

net CS dose on the LEO is half less"
Corrected, thank you.
§ In the paragraph describing the last main outcome

o ListofSymbols: "r" as a spherical shielding radius or outer radius appears two times in the list. Please select only one explanation of "r".
Corrected, thank you.
o Abbreviations:
§ Abbreviation should be explained in their first appearance in the text of the thesis (independently on abstract) + they can be explained again in the extra list. This is not met in all cases (e.g. LEO on page 1, GOES on page 4, TR on page 6, etc.)
Corrected, thank you.
§ the abbreviation list is not full. Explanation of TR, TP, TE, CREME, SOHO, GOES, BFO (maybe more) is missing.
Thank you for pointing this out, the abbreviation list has been extended.
O GCR is usually abbreviation for Galactic cosmic rays including the "s" for plural of rays. In the presented thesis, sometimes is used "GCR" and sometimes "GCRs". I recommend to unify it via using "GCR" everywhere (including abstract, List of abbreviations, and the rest of thesis) and relating to "Galactic cosmic rays".
Corrected, thank you.
o The title of Section 1.1 appears again as the first sentence of the Section. Please delete the sentence "Radiation environment in space.“ and keep the section title only.
Corrected, thank you.
o Section1.1.1,thesecondsentenceofthelastparagraph(page3):use"...the sunspot or Wolf number..." instead of "...the sun-sport or Woolf number"
Corrected, thank you.
o Section1.1.1,the third sentence from the end(page3):Citation is missing and "(formula??)" is used instead. Please correct it.
Corrected, thank you.
o Symbol for steradian is "sr" not "Sr"(Symbol "Sr" is used for Strontium).Please correct it in all of Figures 1.2 a) and b), 1.3 a) and b), 1.4 a) and b).
Corrected, thank you.
o The title of Section 1.1.4 appears again as the first sentence of the Section. Please delete the sentence "Trapped radiation.“ and keep the section title only.
Corrected, thank you.
o Chapter1.2,thirdline:pleaseuse"...in units of gray(symbol: Gy)."in stead of wrong"...in units of Gray Gy." Indeed, the name of the units starts with lowercase (gray) but name of the scientist starts with uppercase (Gray). It should also be explained why the "Gy" is in the sentence, I recommend to use brackets as "(symbol: Gy)".

Corrected, thank you.

o Chapter 1.2, 19th line: please use “... in units of sievert (symbol: Sv).” instead of wrong “... in units of Sivert Sv.”

Corrected, thank you.

o Table1.1,page8:

§ Q=1 for LET<10 and not for LET<1 please correct it

Corrected, thank you

§ The second range of LET must include the edge values, i.e. 10≤LET≤100

Corrected, thank you

§ Usually, the variable LET is in the first column and the functionally dependent Q(LET) is in the second column. Please switch the columns.

Corrected, thank you.

o Please use correct “annual” instead of wrong “anual” in figures 4.1,4.4a),b),4.5,4.6.

The term “annual” is not really correct. The “annual” dose should be calculated as an integral over one year, while the presented results show the monthly averaged dose rate. The “annual” has been removed and dose rates units changed to cSv/year.

o Section1.4.3,firstline:use“probability”insteadof“prob-ability”

Corrected, thank you.

o Chapter2,page17,firstline:comment in brackets“(ref to irradiation facilities)”is not clear to me.

Corrected, thank you

O In Chapter4, the first level subsections (4.1,4.2,etc.) start with a new page while the first level subsections in chapters 1, 2, and 3 start at the same page as the previous subsection. Please unify it.

Thank you for pointing this out, now chapter sections start with a new page all through the manuscript

o Section 4.1, first sentence: specify which figure shows the time dependences of GCR doses (Figure 4.1).

Corrected, thank you.

o Be sure that values are at the same line with their units(it is not the case e.g. on page36, last sentence).

Thank you, now all numbers and units are typed with non-breaking spacing ~.

O Chapter4, page45:missing Figure number and “refcompC” is there instead. Please correct it.

Corrected, thank you.

O Chapter4, page47:missing Figure number and “refcompC” is there instead. Please correct it.

Corrected, thank you.

o Chapter4,page66:missing Figure number and“{refleolab3)” is there instead. Please correct it.

Corrected, thank you.

o Page42:add a reference instead of "[some reference needed?]"
Corrected, thank you.
My questions to be addressed during the thesis defense:

• Special attention in the thesis is paid to neutrons. What is the biological effect of neutrons and why is it much bigger than the biological effect of photons?

The difference in the biological effect is due to secondary particles induced by photos and neutrons. Neutrons produce a lot of secondary protons when they hit the nuclei of atoms. The ionization losses of induced protons and nuclear fragments maximize, when they are slowed down (the Brag peak), so the LET and associated biological effect of the absorbed dose increases. Photons also ionize the medium, but most of the secondary particles are electrons from the outer shells. The energy losses of the electrons are monotonic and do not increase with the decrease in kinetic energy, so the quality factor is equal to 1.

• What GCR models were used in your calculations and why?

In the current work Matthia et al. 2013 was used. The primary motivation was the model simplicity and availability.

• What are the sources of uncertainties related to your calculations and estimates of their values?

Shielding and phantom geometry, the uncertainties in the radiation environment model and the biological effect of space radiation.

• Could be your codes provided for further use of broader public as e.g. an open-source license?

Potentially the access could be provided, but the code should be adopted. For an not-experienced user it look more reasonable to provide an on-line tool based on the calculation results, or merging the results with an existing tool, which provide radiation particle spectra dependent on the orbital parameters.

Summing up, I am convinced that the author Mikhail Dobynde of the presented Ph.D. thesis demonstrated his ability to conduct individual research work and bring valuable results. All main goals defined for this work were fulfilled. For this reason, I recommend that after corrections recommended in this report he will be admitted to the formal thesis defense and delivered the scientific title Ph.D.

Reply to Prof. Baiocco

Author appreciates Prof. Baiocco for his agreement to review the thesis, for reading the manuscript and for his criticism.

The main point that needs to be addressed is the overall editorial style of the manuscript: a careful proofreading is needed, for the many typos, missing or doubled words, references appearing out of parentheses or not correctly appearing (also with the ?? marks generated by LaTeX), Figures not cited in the text, etc. An overall revision of the English language would facilitate the reading: the risk is that the misuse of the language brings to formulations that are wrong or can be easily misunderstood.

Thank you for pointing this out, the spelling was carefully checked and all Latex issues, which have been found, were fixed.

To make only few examples, in the Introduction Chapter, paragraph 1.2:

- "The radiation impact value is characterized by the absorbed dose...." could be formulated as "The radiation impact can be quantified with..." or similar; Gy in units should be in parentheses; "It is equal to energy deposited by a radiation particle..." should be "by radiation", as this is not a dose per particle definition; "specie" is a typo and has always to be corrected with "species"; radiation weighting factors are indicated as wR and not only w; Cousins et al 2013 (which should be in parentheses) does not appear as the right reference for ICRP weighting factors; "An example of such a radiation environment is one inside..." should be "An example of such a radiation environment is the one inside..." and so on.

  Thank you for pointing this out, the corresponding changes have been added to the text.

- A sentence as: "For gamma-rays and neutrons, the radiation quality factor is equal to 1 as they do not have charge" is not correct: it is stated in the same paragraph that the radiation quality factor is dependent on LET. E.g. neutrons with a high LET (the LET of uncharged particles can always be defined based on the LET of the accelerated secondary charged species) will therefore have the corresponding radiation quality factor, different than 1.

That is true, and this is exactly the way how radiation doses for neutrons and gammas have been calculated. However, this statement addressed exactly to neutrons and gammas, not to the induced particles. The phrase has been reformulated to avoid confusion.

- "Indirect irradiation" also is wrongly formulated, and should be corrected with "indirectly ionizing radiation".

Corrected, thank you.

- “Organs with large and complex cells have higher risks associated with higher probability of cell damage” suggests that the size of the cell is a factor determining the outcome of the exposure. Why should it be so? Again, I believe that this is due to a misuse of language more than to wrong knowledge.

By “large cells”, we mean neurons. Since the appropriate reference cannot be provided, this statement was removed to avoid confusion.

Another very important point worth attention appears first in Paragraph 1.3 and later throughout the manuscript: I understand the idea of taking a value of 1 Sv as “reference dose equivalent”, but it has to be kept in mind that career limits are given as effective dose values (including organ weighting factors), when dealing with cancer mortality risk, and as equivalent dose values (particle- and possibly organ- dependent RBE factor multiplied by absorbed dose, measured in mGy-Eq or mGy) when it comes to non- cancer effects.

Indeed, the carrier limit in Russian regulations and dose limits for cancer risk by NASA are defined for the effective dose. However, here a spherical phantom was used, and an additional study required finding the depths in spherical phantom, which correspond to the critical organs. The results from Matthia et al. could not be directly used in our case, because the diameters of the phantoms are different, and the maximal shielding of our phantom is smaller than in Matthia et al. So it was decided to use 1 Sv for the value of the dose equivalent averaged over the phantom. Evidence of such a simplification is that the dose equivalent averaged over the phantom is ~10-15% higher than the effective dose (personal communication with Prof. Shafirkin; Grigoriev et al., 1983). The issue would be addressed in the future, comparing shielding distribution in anthropomorphic and spherical phantom. The corresponding discussion has been added to the text.

Please see NASA Space Flight Human-System Standard - “NASA Standard 3001, Vol.1, Rev. A: Crew Health.” for all details. There is therefore an ambiguity throughout the thesis about the use of dose equivalent to CS as an indicator of radiation effects: according to NASA, the career dose limits for the CS (calculated as average over heart muscle and adjacent arteries) is 1 Gy-Eq.

The second point is also right. It is not correct to compare the Q-weighted dose with the RBE-weighted dose. The RBE(LET) differs from Q(LET), although the dependencies look similar. The primary motivation was address to a career limit in NASA regulations. The limits of effective dose, which is related to cancer risk, are calculated for a specific flight duration for an astronaut of particular age and sex. At the same time, we were looking for a universal limit. However, we believe that the introduced mismatch is of the same order of magnitude as other uncertainties in our calculations, which are related to the phantom, spacecraft, and radiation environment description. RBE(LET)

dependencies for CS would be implemented in further research.
The corresponding discussion has been added to the text.

Most often, though CS doses are cited in the text, it also appears from the Figures that BFO doses have been calculated. Career dose limits are not applicable to BFO doses, as BFO is the main target for short-term effects.
Indeed, the career dose limits are not defined for BFO. That is why, in the text, CS doses of average doses are discussed. The main reason for BFO in figure caption is that is the shielding is approximately the same for the BFO and the CS (personal communication with Prof. Shafirkin). Thus they are defined at similar depth inside the spherical phantom and have similar values. However, after an additional discussion it is decided to replace back "CS" with "BFO" all through the text because of a precise definition and significance of the BFO dose for considering cancer risks. The discussion about CS doses has been added in section 1.2 and 4.1.

In Dobyinde, Shprits, 2019, BFO dose equivalent is calculated for the phantom recommended by the Russian State Standard, and the definition is the same that is adopted in the thesis for CS dose equivalent (see Paragraph 4.1). All this has to be clarified.
The main reason for the identity is approximately the same shielding for the BFO and the CS. Thus they are calculated at the same depth in the spherical phantom.
The main message in Dobynde and Shprits 2019 was that the GCR induce a lot of "indirectly-scattered" particles, especially secondary neutrons, which make a significant contribution to the radiation dose. The BFO dose was selected just as example because it is essential when cancer risk is estimated. However, in section 4.1, the accent was made on the limitations of career expose, which are defined for the CS but not the BFO. For this reason, all through the thesis, CS doses are considered. The "BFO" in figures has been changed to "CS". The corresponding discussion has been and to the manuscript.

please note that the choice of the phantom is motivated clearly in the paper, but not in the thesis
The motivation for the spherical phantom was provided on page 15, starting with "The spherical water phantom is convenient…".

In few occasions, some concepts are also repeated: as examples, in the Literature Review Chapter, when describing the composition of the radiation environment.
Corrected, thank you

A whole paragraph appears twice (page 36 and page 41) in chapter Results

(please amend with the plural) and Discussion.
Corrected, thank you. The reason was that the first two chapters make the core of the Scientific Reports paper, which was inappropriately split in the thesis manuscript.

Though I understand the idea of having a separate Methodology Chapter, it is sometimes not easy to follow the description of results in Chapter 4, as different results are obtained with the different methods previously described. I would suggest to clearly add at the beginning of each Section in Chapter 4 some short summary like: "We present in the following results obtained for .... using the simulation setup described in ... and the radiation environment described in....".
Thank you for the suggestion; a short description has been added at the beginning of the sections.

Also, all formulations like "In the third and the fifth part of the work..." or "All parts of the work ... (second and forth) ... would be published after extra work (fifth)." should be avoided and substituted with "Results presented in 4.3 and 4.5 ....", explicitly referring to section numbers, which is much easier to follow.
Thank you for pointing this out. The issue is corrected all through the manuscript.

More specifically on the different result sections: Section 4.1:

- Please note that there is a reference to some Supplementary materials that might come from the text of an article draft, as no Supplementary materials are available for the thesis. Please amend.
  Corrected, thank you.

Section 4.2:

- Figure 4.5: simulations for multipass particles shown in the same plot do not provide a lot of information, as points are not distinguishable from the 0 dose axis. Maybe they can be shown in an extra Figure?
  Indeed, the contribution of the multipass particles to the net dose is neglectable small comparing to the dose due another particle species. A more detailed plot would not give anything new to the discussion. Generally, the only reason to plot the dependence, and to store associated data during the calculations was to ensure that we don't get artifacts in the secondary particle classification in forward- and backward-scattered. For this reason, I would like to keep the figure as it is.

  Comparing Figure 4.5 and 4.7: I understand simulated data for the net yearly dose to BFO during 2001 solar max or 2010 solar min should be the same. It seems that there are differences: at 0 g/cm2 shielding thickness, BFO dose equivalent for Smin is below 50 mSv in Figure 4.5

and close to 60 mSv in Figure 4.7. Why is this so?

Sorry for the confusion, and thank you for your attention. The reason is that the “50 mSv” plot was calculated with a 25 cm sphere, which was used at the beginning of the work, following Mrigakshi et al. 2013 calculations. Latter, the phantom was changed to a more convenient 17.5 cm sphere. All other plots show calculation results for 17.5 cm phantom. The plot is changed to the correct one now. The misplacing does not affect on the corresponding discussion.

- I think the terminology adopted to divide dose contributions in Figure 4.8 is not quite common in the space radiation community and might be ambiguous: which leptons, mesons and baryons are actually included in the calculations? For baryons, it should be specified “other baryons” as this evidently excludes protons.
- The classification is slightly different from other works because all secondary particles are taken into account. For this reason, categories of leptons and mesons are introduced instead of more convenient electrons, pi-mesons, etc.. Separation of primary particles, secondary neutrons, protons, gammas, and nucleons into separate groups is convenient. Thank you for the suggestion about “baryons”, the corresponding changes are made through the text.

Section 4.3:

- The legend of Figure 4.13 and how such data are referred in the text with colors seem not to be correct (e.g. trapped protons seem not to be given by any green line), please clarify;

  Reference to colors in the text has been corrected, thank you.

- A sentence like: “Thus, it can be concluded that the radiation effect of a 1-year flight to Mars during solar minimum is equal to that of a 2-year flight on the ISS during solar maximum” cannot be accepted as it is. It can be stated that the “cumulative exposure level in dose equivalent” is similar. Again, “identity” is too much for the radiation environment;

  Thank you for pointing this out, the statement has been rephrased.

- The caption of Figure 4.15 is incomplete: the shielding should be specified as it is in the text (where the Figure is wrongly cited as 4.3);

  Thank you, the shielding description has been added to the caption, and figure number has been corrected.

- Figure 4.16: the distinction between primary and secondary particles is not clear: panel a is all primary particles together, and from panel b to h these are all secondary particles? Again, there is the same issue raised for Figure 4.8 about particle nomenclature.

That is correct. For the clarity figure subtitles were extended to "secondary protons", etc.. The motivation on implemented classification was added to methodology section.

- The doubling of the time to make the exposure levels compatible between ISS orbit and flight to Mars scenarios should also be mentioned explicitly in the text and in the caption.
  The doubling of the time was already in the figure legend. However, an additional pointing has been added in the caption.

Section 4.5:

- The term "energy diffusion" (though used in quotation marks) does not seem to be appropriate to me. Maybe something like "(lateral) spread of energy deposition" or similar could be used.
  Thank you for the suggestion, "diffusion" has been changed to "lateral spread".

- In Figure 4.24 the proposed method of "extended ray-tracing" is shown to give better results concerning the shape of dose-depth curve in the near-surface region of the phantom. However, a discrepancy persists between ray-tracing and full MC results (and this is reasonable), but for the highest tested energy (in panel d) the extended ray tracing seems to give result that are more distant from Geant4 simulation than the regular ray tracing, when the depth in the phantom is larger. The reason for this should be discussed. Furthermore, why were these specific proton energies tested? I would rather give values in GeV considering the explored energy range.

The energies have been chosen just to demonstrate the applicability of the proposed methodology. They are the mean energy bin values in logarithmic scale. We believe that the differences between the supposed method and Monte-Carlo calculations are due to "side-scattered" particles discussed in section 4.2. The contribution of these particles increases with the primary particle's energy increase. With the current improvement, the precision in the near-surface layer has been increased. At least two issues: "side-scattered" particles and the back-scattered particle would be addressed in the future.

More generally: results obtained in this thesis work certainly have scientific significance and potential impact for future application, and they can certainly serve as a basis for future studies leading to optimal predictions of space radiation exposures. However, larger efforts should be done to compare results with what is available in the literature, both in terms of simulations and data. This is particularly true for the results reported in sections as 4.1, 4.2 and 4.3 (while for instance section 4.4 already benefits from the comparison with MATROSHKA-R data and is more naturally included in a collaborative framework).

The chapter Conclusions can offer a good chance to critically discuss some of the aspects of this work that I've highlighted above, as the choice of using dose equivalent values for exposure career limits to determine the optimal flight conditions. Also, a reformulation is needed concerning the conclusions that are drawn from results presented in 4.3: the similarity of radiation environment in LEO and interplanetary flights is certainly a big advantage if we perform radiobiological research on the ISS and we want to obtain results of interest in view of a deep space mission. Nevertheless, there is a number of feasibility issues to be addressed to perform this kind of research on orbit, and this is not even mentioned. A sentence like: "There is a number of advantages for radiological studies on LEO comparing to on-ground experiments." cannot be accepted if not integrating the discussion in this sense.
Thank you for pointing this out. The discussion in sections 4.1 and 4.2 has been extended.

Concluding, a careful review of the manuscript is needed, addressing the issues raised in the present report. The scientific content of the manuscript in terms of obtained results is already of high level, and the review should be mainly focused at increasing the editorial style of the manuscript and including some critical points in the discussion of results.

Reply to Prof. Fortin

Author appreciates Prof. Fortin for his agreement to review the thesis, for reading the manuscript and for his criticism.

The introduction is rather long and includes a significant amount of literature information that should be moved to the literature review chapter.

The literature review part has been extended and now includes more papers in the discussion.

The document needs more extensive proofs on the verification of the results. There are only a few briefs instances where comparisons with previous work are mentioned and they do not provide significant evidence on the validity of the presented results.

Results in section 4.1 are compared in detail with Matthia et al. and Slaba et al. publications, which address the most similar problems with most up to date methods. An additional comparison was made with results in Denisov et al., 2011 Kuznetsov et al., 2012. Results for the neutron dose in section 4.2 have been compared to Denisov et al., 2011; Kuznetsov et al., 2012; and Ballarini et al., 2006.

The problem in comparing results in section 4.3 with other work is differences in the calculated values. The LET-dependent dose spectrum is the most standard output of the experimental measurements. The corresponding calculations are currently running and would be added in the publication in the Life Science and Space Research journal at the revision stage. A broad comparison with other works is made in section 4.4 provides. Section 4.5 addresses the limitations of ray-tracing methods and approaches to overcome them. The results cannot be compared to any other works since these issues have not been addressed before.

Reply to Prof. Ouerdane

Author appreciates Prof. Ouerdane for his agreement to review the thesis, for reading the manuscript and for his criticism.

The numerical data obtained with GEANT4 had to be processed to be productively analyzed. The actual processing is mentioned in the thesis manuscript but there is a lack of detail. It is expected that Mr. Dobynde provides more detail on the data processing.

A more detailed description was added to the methodology section, thank you.

Given the complexity of the physical radiation-matter interaction problem and the amount of experimental data now available, would a machine learning approach be of added value to compute and simulate radiation doses considering different sources, more realistic geometries, and solar activity?

Unfortunately, the current level of our knowledge can not suppose a way to implement machine learning to the radiation dose assessment during the space flight. The machine learning approach is already implemented in the reconstruction of the sate of electron radiation belt during storms. Probably, the machine learning approach can be implemented at the stage of selecting most resistant candidates for missions, where the risk factors are determined.

References

Ballarini, F., Battistoni, G., Cerutti, F., Fassò, A., Ferrari, A., Gadioli, E., … Zankl, M. (2006). GCR and SPE organ doses in deep space with different shielding: Monte Carlo simulations based on the FLUKA code coupled to anthropomorphic phantoms. Advances in Space Research, 37(9), 1791–1797. https://doi.org/10.1016/j.asr.2006.03.007

Denisov, A. N., Kuznetsov, N. V., Nymmik, R. A., Panasyuk, M. I., & Sobolevsky, N. M. (2011). Assessment of the radiation environment on the Moon. Acta Astronautica, 68(9–10), 1440–1447. https://doi.org/10.1016/j.actaastro.2010.01.025

Grigoriev, A. I., Kovalev, E. E., Kovarskiy, L. M., & Kudryashov, E. I. (1983). Model of human body forcalculation of tissue dose. GOST25645.203-83

Kuznetsov, N. V., Nymmik, R. A., Panasyuk, M. I., Denisov, A. N., & Sobolevsky, N. M. (2012). Estimation of radiation risk for astronauts on the Moon. Cosmic Research, 50(3), 216–220. https://doi.org/10.1134/S0010952512030057

Matthiä, D., Berger, T., & Reitz, G. (2013). Organ shielding and doses in Low-Earth orbit calculated for spherical and anthropomorphic phantoms. Advances in Space Research, 52(3), 528–535. https://doi.org/10.1016/j.asr.2013.03.025

Mrigakshi A.I., Matthia D., Berger T., Reitz G., Wimmer-Schweingruber R.F., Estimation of Galactic Cosmic Ray exposure inside and outside the Earth's magnetosphere during the recent solar minimum between solar cycles 23 and 24, Advances in Space Research 52, 979–987 (2013). https://doi.org/10.1016/j.asr.2013.05.007

Nymmik, R. A. (1996). Models describing solar cosmic ray events. Radiation Measurements, 26(3 SPEC. ISS.), 417–420. https://doi.org/10.1016/1350-4487(96)00052-2

Russian State Standard. Interaction of ionizing radiation with matter. Chemical composition of the tissue-equivalent matter. (2003). GOST-18622-79.