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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Mikhail Dobynde

PhD Program: Engineering systems

Title of Thesis: Radiation Shielding of Astronauts during Interplanetary Flights

Supervisor: Prof. Rupert Gerzer

Date of Thesis Defense: 17 February 2020

Name of the Reviewer: Giorgio Baiocco

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:** Giorgio Baiocco January 19, 2020 **Date: 19-01-2020**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense. *If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.*
Reviewer's Report
Reviewers report should contain the following items: • Brief evaluation of the thesis quality and overall structure of the dissertation. • The relevance of the topic of dissertation work to its actual content • The relevance of the methods used in the dissertation • The scientific significance of the results obtained and their compliance with the international level and current state of the art • The relevance of the obtained results to applications (if applicable) • The quality of publications The summary of issues to be addressed before/during the thesis defense

The thesis presented by the candidate includes a large variety of simulation results of great interest in the general context of space radiation shielding for interplanetary flights. The topic is undoubtedly of great relevance, different methods (all of relevance and all widely adopted by the space radiation community) are used and discussed, also highlighting their differences and limitations.

The candidate lists three published papers: results from the first two (both of good quality, with the candidate as first author) are included and discussed in the thesis. Two more papers reporting results included in the thesis are cited as under review.

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.

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

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. 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. 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. In Dobyinde, Shprits, 2019, BFO dose equivalent is calculated for the phantom recommended by the Russian State Standard (please note that the choice of the phantom is motivated clearly in the paper, but not in the thesis), 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.

In few occasions, some concepts are also repeated: as examples, in the Literature Review Chapter, when describing the composition of the radiation environment. A whole paragraph appears twice (page 36 and page 41) in chapter Result**s** (please amend with the plural) and Discussion.

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….*". 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.

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.

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?
- 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/cm^2 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?
- 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.

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;
- 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;
- 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);
- 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. 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.

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.
- 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.

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.

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.

Provisional Recommendation
☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*
☑ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*
☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*