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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: Mikhail Panasyuk

I confirm the absence of any conflict of interest	**Signature:** **Date: 17.01.2020**

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

Radiation is one of the most dangerous phenomena in outer space, which is caused by the existence of charged particles of different nature. Radiation not only creates problems for the" survivability " of spacecraft themselves, but also for humans in space. The problem of radiation hazard of long-term space flights continues to be relevant. This is a consequence of the progress of research on radiation in space – obtaining new knowledge about the physical characteristics of multicomponent radiation fields in space and the mechanisms of their impact on biological structures, materials and components of space technology. Galactic (GCR) and solar cosmic rays (Solar Energetic Particles – SEP) are the main factors of radiation hazard during interplanetary flights. In addition to these components of cosmic ionizing radiation , high - energy particles, mainly electrons and protons, trapped in the magnetic field of our planet - the Earth's radiation belts-have a dominant influence on the safety of space flights near the Earth.. Therefore, the problem of radiation safety of space flights is a multi-factor problem, the solution of which depends on an adequate assessment of specific radiation fields, which in turn depend on the heliophysical and geophysical conditions in the space environment, on the calendar time of the space mission, and on the design features of the spacecraft itself. To assess the specific physical values of radiation effects on both spacecraft elements and biological objects (dose effects, single failures in microchips, exposure of particles at the molecular level and on the nervous system of complex biological objects, etc.), it is necessary to monitor space radiation directly in space, as well as to model the fields of space radiation and its effects on condensed matter.

Within the framework of the above, I would like to emphasize the following aspects of the presented thesis, which, in my opinion, really represent a significant contribution to the development of this topic.

• The relevance of the topic of dissertation work to its actual content

The topic of the dissertation work is relevant to its actual content and ongoing research activities. Interplanetary space missions and particularly crewed missions to Moon and to Mars, as well as the Gateway near-Moon space station are announced by different space agencies. One of the main concerns about mission safety is related to the damage due to space radiation. The large energy range of radiation particles, variety of particles species and differences in time variation require different and contradictive strategies of radiation shielding that should be applied to minimize associated risks. With the current work author clear demonstrate the optimal flight condition for the past solar cycle and provide a deep analyze of radiation composition inside the spacecraft. The methodology of the research makes it easily to use results of performed Monte-Carlo calculations for assessing radiation doses for other time periods and flight conditions, particularly for radiation dose prediction, as soon as necessary radiation environment model would be developed.

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• The scientific significance of the results obtained and their compliance with the international level and current state of the art

All parts of the work are made using modern methods, fulfill the knowledge about the radiation exposure of astronauts and have important scientific value. Particularly, results in section 4.1 clearly indicate the optimal time and shielding conditions for a long-term flight to Mars, which are extremely important for mission planning and can be use by space agencies. Results in section 4.3 demonstrate time and shielding conditions that minimize differences of the radiation environment on the ISS and outside of the Earth magnetosphere. This is important for extrapolation radiobiological experience obtained on the ISS beyond the magnetosphere of the Earth. The results in section 4.2 and 4.4 give a deep view on the radiation dose composition inside spacecraft and astronauts phantom. Results in section 4.5 clearly show the limitations of the shielding function method for dose calculations and possible way to overcome the limitations is supposed.

• The relevance of the obtained results to applications

The results in section 4.1 can be used by space agencies for interplanetary mission planning. The results in section 4.4 could be used for fast radiation dose assessment in a spacecraft with complex geometry. The limitations of the method are discussed in section 4.5.

• The quality of publications

The results or the PhD research have been published in high-level pre-reviewed journals: two papers in Life Science in Space Research and one paper in Space Weather. Additionally, two papers under review in Life Science in Space Research and Scientific Reports.

• Comments and criticisms

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.

In addition, there are less significant comments.

There are some points just to correct.

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

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

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

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·cm^2. Thus, most risk due to SEPs is associated with extra vehicular activity (EVA).

See my main comment above. It is not correct.

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.

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

However, my comments do not affect the overall assessment of the thesis, which is the result of highly qualified work of the author and I have no doubts about awarding him a PhD degree.

Recommendation

I definitely recommend that the candidate should defend the thesis by means of a formal thesis defense