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Space Exploration: Where we have been, Where we are and Where we are going – A human perspective

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NASA is moving forward towards the agency's new vision for space exploration in the 21st Century encompassing a broad range of human and robotic missions including missions to Moon, Mars and beyond. Exposure from the hazards of severe space radiation in deep space long duration missions is 'the show stopper.' Langley has developed state-of-the-art radiation protection and shielding technology for space missions. The payload penalty demands a very stringent requirement on the design of the spacecrafts for human deep space missions. The exploration beyond low Earth orbit (LEO) to enable routine access to more interesting regions of space will require protection from the hazards of the accumulated exposures of space radiation, Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE), and minimizing the production of secondary radiation is a great advantage. The better understanding of radiation environment (GCR & SPE) and their interaction is a key to the success of the program due to the vital role and importance of cosmic rays for space missions.

1. Introduction

On May 25, 1961 President Kennedy's announcement to put a man on the moon and bring him back safely before the end of the decade set the advent of human exploration of space for NASA culminating to the landing on the Moon on July 16, 1969. Space exploration continued mainly by space transportation system (STS) missions. On January 14, 2004 President George Bush set up a new vision for NASA. He articulated agency's vision for space exploration in the 21st Century, encompassing broad range of human and robotic missions including missions to Moon, Mars and beyond. As a result, there is a focus on long duration space missions. NASA, as ever, is committed to the safety of the missions and the crew. There is an overwhelming emphasis on the reliability issues for space missions and the habitat. The cost effective design of the spacecraft demands a very stringent requirement on the optimization process. Exposure from the hazards of severe space radiation in deep space long duration missions is 'the show stopper'. Thus protection from the hazards of severe space radiation is of paramount importance to new vision. It is envisioned to have long duration human presence in Moon for deep space exploration. As NASA is looking forward to exploration in deep space, there is a need to go beyond current technology to the technology of the future. Faced with a limited budget and an expanding space exploration program, the old way of doing business is inadequate and NASA requires revolutionary technologies to make advances.

An enabling technology for the exploration, the development, and the commercialization of space is a cost-effective means of reducing the health risks from exposures to galactic cosmic rays (GCR) and a possible solar particle event (SPE). This has been a well-recognized challenge and a critical enabling technology for exploration in which astronaut health effects are of principal concern.

In the present paper, we will first review the underlying quantities to be considered and their implementation into the design process. We will then use this development to examine a typical Lunar and a Lunar Gateway mission. In this application we will consider a 30-day mission for casual and career astronauts for a couple of missions a year for a period of ten-year period. The analysis is also provided for two Mars missions. Clearly future developments will require a more complex mission scenario and optimization across a more complex array of habitats and vehicles.

2. Discussion

Shield mass can be a high cost factor in system designs for the long-term operations required and optimization methods in the design process will be critical to cost-effective progress in space development [1,2]. Limiting the time of transfer to duty station or the mission time within the solar cycle as well as the choice of materials used in construction can reduce the shield mass required on specific missions [3]. Unfortunately, adequate optimization procedures have not been available to minimize the mass and the associated costs for a given mission scenario.

Much of the protection within a space structure is provided by the structural elements, onboard materials, and equipment required for other purposes and the means of making the best choice of materials among various options is critical to the protective qualities of the overall design. Multifunctionality of materials (for example, structural elements which have good shielding properties) will be common in the optimization process. Furthermore, the design decisions cannot be made in a vacuum and multidisciplinary design methods need to be developed. The need for multifunctional/multidisciplinary design techniques was identified as critical to the cost-effective development of space several years ago and expanded on recently.

In the past an amount of exposure was assigned to each mission segment and developed as a subjective strategy with relative improvements of costs through material trades dependent on off-optimum design solutions. It is the purpose of the present study to develop the necessary optimization methods for minimum mass determinations to be used in performing trade studies to enable objective trade reduction costs since strategies for meeting exposure constraints are optimized over the entire mission architecture for each trade. In addition to optimized design trades, we will also consider the implementation of the principle of as low as reasonably achievable (ALARA) required by federal regulation and normally ignored in mission design studies. The ALARA principle will be met by added protection of the crew quarters where members will spend a significant fraction of each day sleeping. The main crew quarter design will also be used as the shelter from potential solar particle events during the mission. In this respect, we assume an adequate strategy for exposure limitation during extra vehicular activity (EVA) is available and the design is mainly the habitable volume and crew quarter/SPE shelter.

The present exposure constraints used in the space program are recommended for low Earth orbit (LEO) operations by the National Council on Radiation Protection [4] and approved by the NASA Administrator and OSHA. There are no limits for deep space operations due to the unusual composition of the GCR and the resultant uncertainties in associated health risks. The NCRP did recommend that the limits for low earth orbit (LEO) operations could be used as a guide in deep space operational studies [4]. New exposure recommendations are now approved by the NCRP and the new LEO limits, given for the three critical organs of skin, ocular lens, and blood forming organ (BFO), will be used herein recognizing the associated uncertainties. We use dose equivalent for the Gy-Eq since insufficient data will not allow Gy-Eq evaluation at this time.

In the present work, the optimized mission will be taken as the minimum mass to meet mission requirements and not exceed the exposure constraints [4]. The present design considerations are for the main habitable areas. The volume limited crew quarters where a large fraction of personal time is spent will have added protection to further reduce exposures (ALARA) and will also be designed to provide the shelter from a solar particle event.

Aside from the radiation health risks, the psychological well being and its impact on crew performance also affects the shield design [1, 3]. Crew performance level is related in part to the length of the mission and the volume of the work/living areas of the spacecraft. Rather small volumes are useful over short time periods but long missions require sufficient space for a crew to perform at reasonable levels. We will use the optimal design for the habitable volume and the Tolerable design [1, 3] for the crew quarters which will also serve as the SPE shelter.

In addition to the trapped radiations and the galactic cosmic rays able to penetrate the geomagnetic field to LEO, there are occasional solar particle events able to penetrate the geomagnetic field. The solar particle source is mainly composed of protons of similar quality as the trapped protons. The implications of the galactic cosmic ray exposures on LEO operations have not been fully evaluated with respect to exposure limitations.

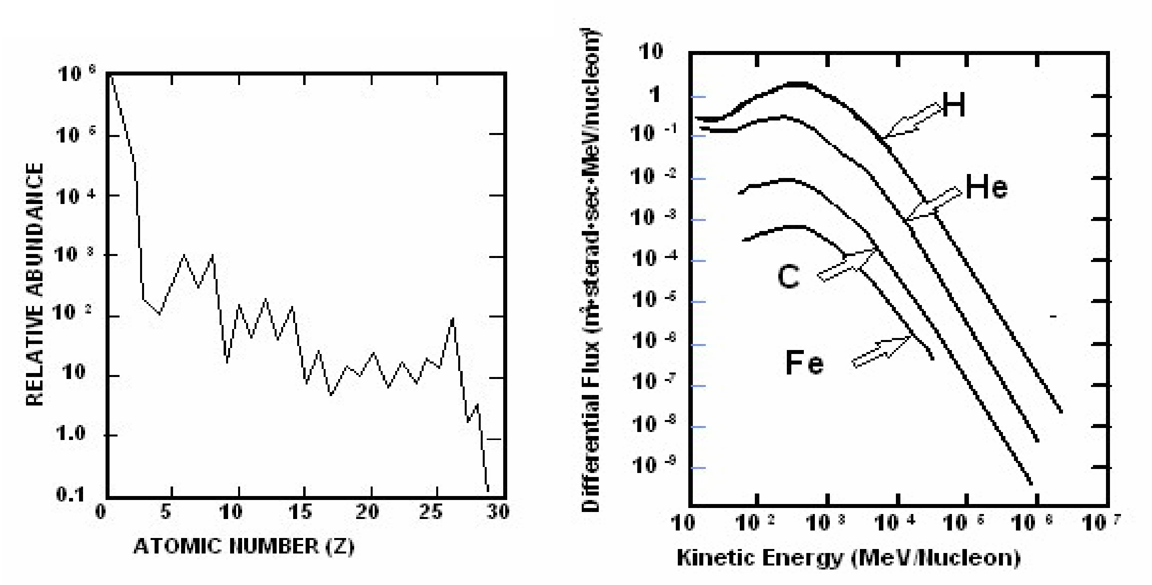

Figure 1. Galactic Cosmic Ray in Charge (Left Figure) and Energy (Right Figure).

Beyond the geomagnetospheric, the galactic cosmic rays (GCR) are the dominant long-term exposure hazard. Generally for deep space operations, the provision of protection from galactic cosmic rays will provide most, if not all, the protection required from solar particle events. The GCR are ions of every known element with spectra spanning rather modest energies to very high energies (Figure 1). Although space radiation mostly consists of protons and helium ions, the high-energy heavy ions or HZE ions deliver a large fraction of the dose equivalent. The linear energy transfer (LET) of a given ion is proportional to the square of the charge and a very broad range of LET is encountered beyond LEO for which there is little biological data.

To demonstrate the method, we consider a 30 day lunar mission for casual and career astronauts. We assume that casual astronauts make a single mission to Moon on the other hand career astronauts make a couple of missions a year for a period expanding ten years with a mixed crew of six in both the cases. The optimum volume of living space is taken as 114 m^3 and crew age set at the youngest female. It is assumed that the living space is a right circular cylinder 2.2 m high. Shield optimization was investigated for a variety of

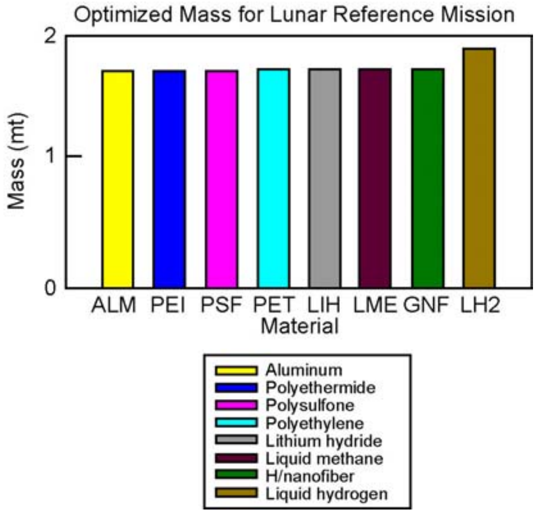

Figure 2 a. Radiation shielding for casual astronauts

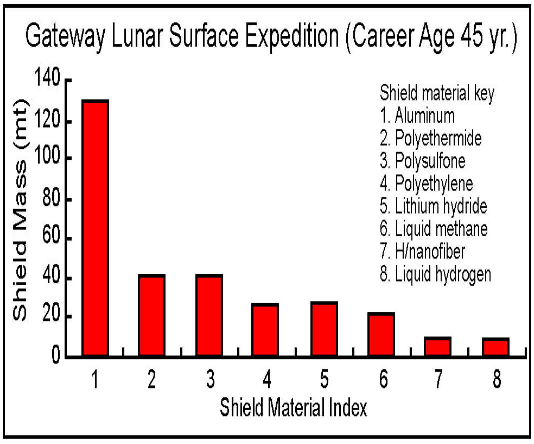

Figure 2 b. Radiation shielding for career astronauts

materials: Aluminum, polyethermide, polysulfone, polyehelene, lithium hydride, liquid methane, hydrogenated nanofiber, liquid hydrogen. The reason for the choice of materials is that there is increasing hydrogen content in the materials as we go down the list from Aluminum to liquid hydrogen. We have established that hydrogen is a better shielding material. As a result, the more the hydrogen content the better the material is expected to perform for GCR radiation shielding in space. Figure (2a) shows optimized mass for single Lunar mission for casual astronauts. Notice that for a single Moon mission the choice of the material is not so important, but for long duration space missions (Figure 2b), as for career astronauts, graphite nanofibers and liquid hydrogen out perform other materials. Although this is not the exact geometry and only the shield wall is represented we see a large impact on the payload in the design. For two (1 year and 2 years) Mars mission [5] (not shown due to space limitation) shield optimization was obtained *only* for graphite nanofibers and liquid hydrogen.

3. Conclusions

Current technology is adequate for single lunar mission for casual astronauts. Revolutionary shielding materials and concomitant technology need to be developed for career astronauts in long duration/ deep space human missions.

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