A RADIATION SAFETY ANALYSIS FOR LUNAR LAVA TUBES

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Introduction. An analysis of radiation safety issues on lunar lava tubes as potential habitats has been performed. Lava tubes are basically formed when an active low viscosity lava flow develops a continuous and hard crust, which thickens and forms a roof above the still flowing lava stream, and at the end of the extrusion period an empty flow channel now free from molten magma is left [1]. Lava tubes are commonly observed on the Earth [2], on basaltic volcanic terrains, with typical sizes of the order of 1-2 km of length, and few meters for cross-sectional parameters (i.e. height and width). Under lunar conditions (lower gravity field, absence of atmosphere), lava channels and tubes are at least an order of magnitude larger in each size dimension [3], i.e. hundreds of meters wide by hundreds of meters or more deep and tenths of kilometers long. For many years [1-3] it has been suggested that these natural cavities on the Moon could provide an ideal location for a manned lunar base, by providing shelter from various natural hazards, such as cosmic rays radiation, meteorites, micrometeorites impacts, and impact crater ejecta for example, and also providing a natural environmental control, with a nearly constant temperature of –20° C unlike that of the lunar surface showing extreme variation in its diurnal cycle. The purpose of this work is an assessment of the lunar lava tube radiation characteristics and an evaluation of the their actual safety features.

Lava Tubes Geology. The formation of lava tubes is generally associated to the formation of “sinuous rilles” [4], frequently observed on the lunar basalt surface, especially in the maria floors, which formed from high extrusion and very low viscosity magma which filled the existing basins. In contrast to the so numerous flow channels in the form of sinuous rilles, real lava tubes cannot be easily observed on the Moon, for the reason of being subsurface objects, therefore unobservable in surface imagery, and only those with at least a partially collapsed roof are observable. Moreover, lunar surface imagery is at most at medium resolution, so rilles or tubes smaller than few meters wide are not observable with present lunar imagery. A catalog of lava tube candidates has been obtained by analyzing Lunar Orbiter and Apollo imagery along lunar rilles on the lunar nearside [5], and more than 90 candidates were identified in maria, namely Oceanus Procellarum, Mare Imbrium, Mare Serenitatis and Mare Tranquillitatis, as discontinuous rilles alternating between open lava channel segments and roofed-over segments. This catalog provided a large lunar lava tube data set, from which typical values for minimum, average and maximum for lunar lava tube size parameters have been extracted and incorporated into the transport calculation. The “minimum” values are such with respect to the currently available imagery, with a tube a roof thickness of e.g. 3 m being unobservable.

Scenarios. The analysis has been performed considering radiation from galactic cosmic rays (GCR) interacting with the lunar surface. The surface has been modeled as a 5 m regolith layer, followed by rock. The regolith density profile has been obtained by combining data from groundbased radio-physical measurements and from in-situ analysis data from the Luna, Surveyor and Apollo missions, as modeled in [6], whereas for the rock layer a constant value of 3.3 g/cm3 has been used as typical of mare basalt rock. The composition has been adopted as the same for both surface and rock layers, and has been chosen as an average of the Apollo 12 surface samples [7, 8, 9] taken at the Oceanus Procellarum landing site, the region with the largest number of lava tube candidates in the catalog. Two different scenarios have been considered, namely a Lunar Night (Tsurface = 100 K) and a Lunar Day (Tsurface = 400 K) scenario, with temperature profiles for regolith and rock as from data from the Apollo 15 and Apollo 17 landing sites measurements [10, 11, 12].

Analysis. For the initial conditions a primary spectrum of GCR (p, α, HZE) for Solar Minimum conditions modulated at 510 MV has been adopted as background radiation, and a spectrum with particle fluxes equivalent to four times the intensity of the 29 September 1989 event has been adopted for Solar Particle Events (p). All primary particles heavier than protons have been approximated as individual nucleons, e.g. α He4 nuclei have been transported as 4 individual protons. Radiation profiles given by natural and induced radioactivity (α, β, γ) have been taken into account. Particles (p, n, K+ , K–, π+, π–, µ+ , µ–, e+, e–, γ) have been transported with the three-dimensional Monte Carlo transport code FLUKA [13]. The evaluation of the radiation safety-related quantities, namely the Effective Dose (E) and the Ambient Dose Equivalent (H*10), from particle fluence has been performed with the conversion coefficients given in ref. [14], whereas the physical quantity Absorbed Dose (D) has been obtained by rescaling with the use of the ICRP60 [15] radiation weighting factors w. Both downward and upward (backscattering) particles have been considered in the dose evaluation, so the results obtained are to be taken as radiation exposure upper limits.
Results. No significant differences in the results have been observed between the Lunar Night and the Lunar Day scenarios. After 6 m of depth no effects of radiation due to or induced by GCR in both quiet and disturbed scenarios are observable in the simulation, and after far less than 1 m no effects of radiation due to or induced by SPE particles are observable. Natural and induced radioactivity seems not to play a significant role in the lava tube exposures. Mesons can interact in a quite dense material like lunar rocks before decay, and this is the reason why this usual component, mainly $\mu^+$,$\mu^-$, is not present at larger depths. As a by-product of the transport results, the particle fluence from arriving GCR particles and from upward backscattering just at Moon surface and the relative dose equivalents have been obtained. Also in the very shallow and presently unobservable lunar lava tubes, with roof thickness of the order of 1-2 m, the doses are well below the monthly, annual and career limits given by NCRP 132 [16]. The radiation safety of lunar lava tubes environments has been demonstrated.

References: