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Lunar Lava Tube Radiation Safety Analysis

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For many years it has been suggested that lava tubes on the Moon could provide an ideal location for a manned lunar base, by providing shelter from various natural hazards, such as cosmic radiation, meteorites, micrometeoroids, and impact crater ejecta, and also providing a natural environmental control, with a nearly constant temperature, unlike that of the lunar surface showing extreme variation in its diurnal cycle. An analysis of radiation safety issues on lunar lava tubes has been performed by considering radiation from galactic cosmic rays (GCR) and Solar Particle Events (SPE) interacting with the lunar surface, modeled as a regolith layer and rock. The chemical composition has been chosen as typical of the lunar regions where the largest number of lava tube candidates are found. Particles have been transported all through the regolith and the rock, and received particles flux and doses have been calculated. The radiation safety of lunar lava tubes environments has been demonstrated.

INTRODUCTION

An analysis of the radiation safety issues of 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 due to radiative cooling of its outermost part, which thickens and forms a solid roof above the still flowing lava stream. At the end of the extrusion period, if the lava flow conditions were ideal in terms of viscosity, temperature, supply rate and velocity, an empty flow channel now free from molten magma is left[1)], in the form of an approximately cylindrical-shape tunnel below the surface. Lava tubes are commonly observed on the Earth[2)], on basaltic volcanic terrains like those of Hawaii, Oregon and Washington states, 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 hundred of meters or more deep and tenths of kilometers long. Since long time it has been suggested[1–3)] that these natural cavities on the Moon could provide an ideal location for a manned lunar base (see Fig. 1), 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 analysis performed in this work is limited to the radiation-related properties, so the purpose of this work is an assessment of the lunar lava tube radiation environment and an evaluation of the actual radiation safety features.

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THE LAVA TUBES

The formation of lava tubes is generally associated with the formation of "sinuous rilles"[4)], valleys 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

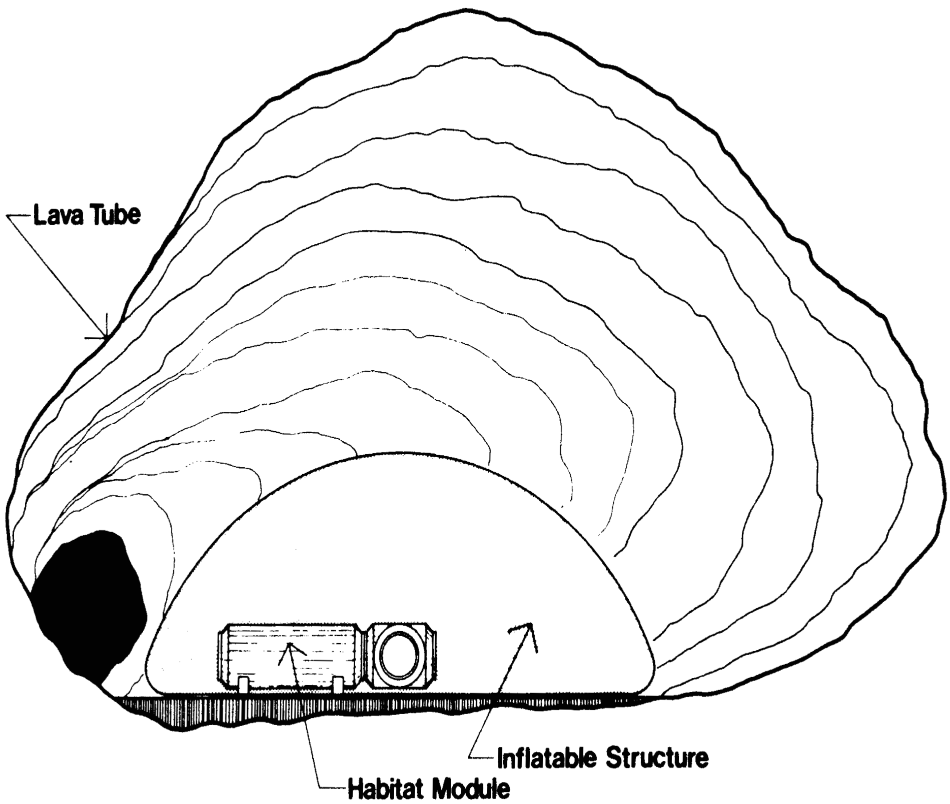

Fig. 1. Unpressurized lava tube cross-section with inflatable structure and habitat module[22)]

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 best at medium resolution[5)], so rilles or tubes smaller than few meters wide are not observable with present lunar imagery. A catalog of lava tube candidates has been created by analyzing Lunar Orbiter and Apollo imagery along lunar rilles on the lunar nearside[6)], and more than 90 candidates were identified in some of the lunar maria, namely Oceanus Procellarum, Mare Imbrium, Mare Serenitatis and Mare Tranquillitatis, as discontinuous rilles alternating between open lava channel segments and roofed-over segments (see Fig. 2). An estimation of the cross-sectional size of the observed lava tubes was performed by projecting the walls of the adjacent rille segments all along the roofed-over segments, whereas the length were measured directly from the imagery and the roof thickness was estimated through the craters superimposed to the uncollapsed roof. This catalog provided a large lunar lava tube data set, from which parameters typical for minimum, average and maximum values for lunar lava tube size have been extracted. The "minimum" values are such with respect to the currently available imagery, with tubes with a roof thickness of e.g. 3 m being currently unobservable.

RADIATION ANALYSIS SCENARIO

The analysis has been performed by considering ionizing radiation particles 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 radiophysical measurements and from in-situ analysis data from the Luna, Surveyor and Apollo missions[7)], whereas for the rock layer a constant value of 3.3 g/cm^3 has been used as typical of mare basalt rock[8)]. The same composition has been adopted for both surface and rock layers, and has been chosen as an average of the Apollo 12 surface samples[8–10)], 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 ($T_{surface}$ = 100 K) and a Lunar Day ($T_{surface}$ = 400 K) scenario, with temperature profiles for regolith and rock extrapolated from data from the Apollo 15 and Apollo 17 landing sites measurements[11–13)]. The range of describing parameters provided by the existing database of lunar lava tubes has been incorporated into the transport calculation. The primary effect of the temperature variation is seen in

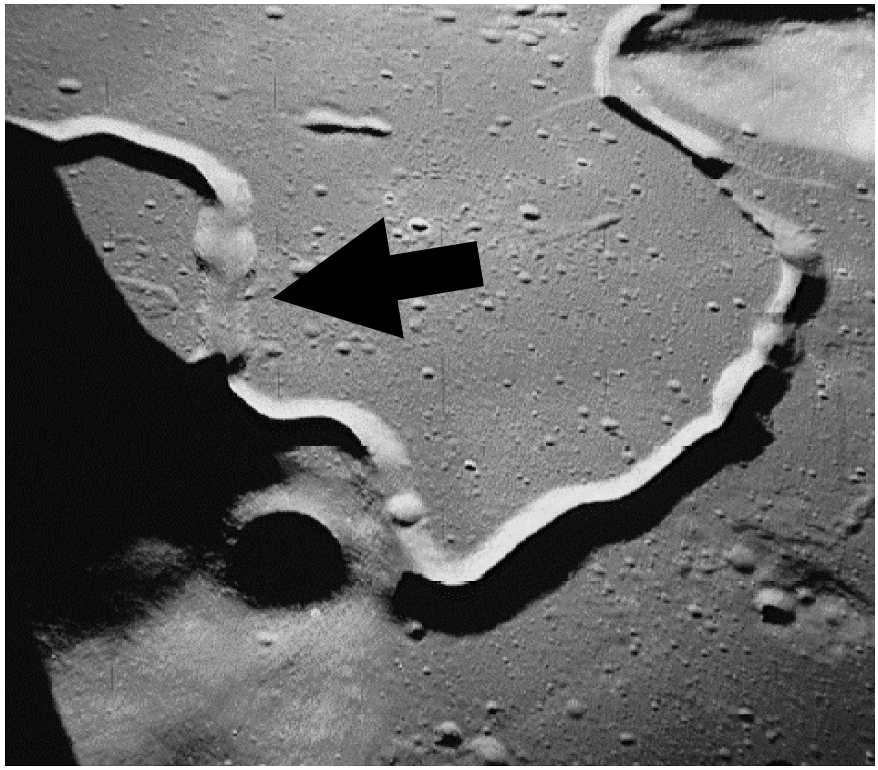

Fig. 2. Enlargement of an uncollapsed lava tube near the crater Gruithuisen (from Lunar Orbiter frame No. LO-V-182-M)

the neutron spectrum near thermal energies and is of no consequences to human protection.

As for the initial conditions, a primary spectrum of GCR (p, α, HZE) for Solar Minimum conditions[14] modulated at 510 MV Heliocentric Potential has been adopted as background radiation, and a spectrum with particle fluxes equivalent to four times the intensity of the 29 September 1989 event[15] has been adopted for Solar Particle Events (p). All primary particles heavier than protons have been approximated as individual nucleons, e.g. He^4 nuclei have been transported as 4 individual protons. Radiation profiles given by natural and induced radioactivity (α, β, γ) have been taken into account. All known particles have been transported with the three-dimensional Monte Carlo transport code FLUKA[16]. The evaluation of the radiation safety-related quantities, used both in environmental assessments and in health-based procedures[17–18], namely the Effective Dose (E) and the Ambient Dose Equivalent (H*10), has been performed with the conversion coefficients by Pelliccioni[19] from particle fluence. The physical quantity Absorbed Dose (D) has been also obtained, by inversely using the ICRP60 radiation-weighting factors[20] w_r. Although there are no NASA standards for human exposure in deep space due to the large biological uncertainties, the recommended limits for LEO operations[21] are used as a guide to deep space shield design.

RESULTS

The results for the Effective Dose from GCR are shown in Fig. 3. The use of the Ambient Dose (H*10) underestimates the Effective Dose (E) by 10% (H*10=0.272 Sv/yr vs. E=0.297 Sv/yr at the point of the maximum dose rate). 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 GCRs 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. The probability of a meson nuclear interaction is greater than the probability of decay in dense materials like lunar material, which is why the $\mu^{\pm}$ component is not present at large depths of the moon. 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

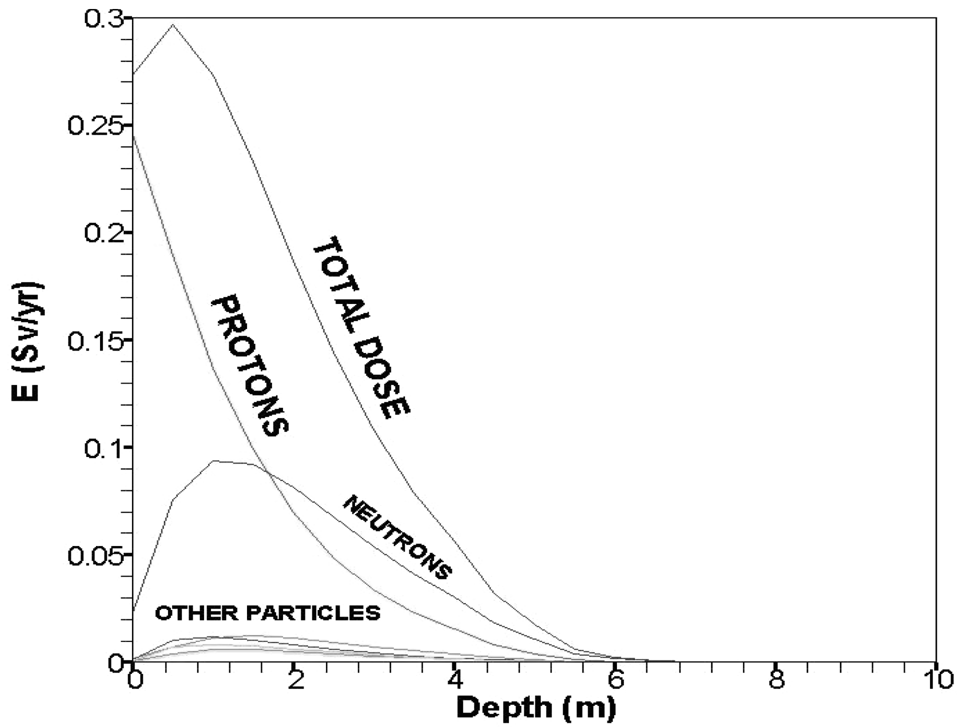

Fig. 3. Results for Effective Dose (E) inside a lava tube (OTHER PARTICLES - i.e. all kinds of particles other than Protons and Neutrons transported by the FLUKA code, namely electrons, positrons, photons, pions, muons, kaons, deuterons, etc.)

limits[21] given by NCRP 132. The radiation safety of lunar lava tubes environments has been demonstrated.

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