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Radiation damage of polyethylene exposed in the stratosphere at an altitude of 40 km

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ABSTRACT

Low-density polyethylene (LDPE) films were exposed at an altitude of 40 km over a 3 day NASA stratospheric balloon mission from Alice Springs, Australia. The radiation damage, oxidation and nitration in the LDPE films exposed in stratosphere were measured using ESR, FTIR and XPS spectroscopy. The results were compared with those from samples stored on the ground and exposed in a laboratory plasma. The types of free radicals, unsaturated hydrocarbon groups, oxygen-containing and nitrogen-containing groups in LDPE film exposed in the stratosphere and at the Earth's surface are different. The radiation damage in films exposed in the stratosphere are observed in the entire film due to the penetration of high energy cosmic rays through their thickness, while the radiation damage in films exposed on the ground is caused by sunlight penetrating into only a thin surface layer. A similarly thin layer of the film is damaged by exposure to plasma due to the low energy of the plasma particles. The intensity of oxidation and nitration of LDPE films reflects the difference of atmospheric pressure on the ground and in the stratosphere. The high-density radiation damage of the LDPE films above the ozone layer in the stratosphere is caused by primary cosmic rays as well as collision induced cosmic ray air showers, and is consistent with the measured flux of cosmic radiation. The results show, that stratospheric flights can be used to simulate the effects of space environments during interplanet space flights for the purposes of investigating the degradation of polymer materials.

1. Introduction

The environment in free space is destructive for materials. In-space conditions such as high vacuum, extreme temperature cycling and exposure to high energy cosmic rays including protons and α-particles, electrons, γ-rays, X-rays, UV and VUV light, damage the materials from which space ships, space stations and satellites are constructed. A number of investigations of exposure of different materials are being carried out on the International Space Station and other satellites to acquire knowledge of the destructive processes in space. These experiments are quite expensive and samples are limited in mass and volume by the cost of transporting materials into space and by the volume of the space station, while the exposure time is limited by the duration of the space flight.

Another way of investigating damage to materials in space is to expose the samples during stratospheric balloon flights. When a balloon is above the ozone layer, the irradiations to which the materials are exposed are essentially those encountered in free space. The intensity of space irradiations is lower, than for satellites in Low Earth Orbit (LEO) due to absorbance in the top atmosphere, but higher than on the Earth's surface. The most important factor for material destruction in LEO is the flux of atomic oxygen, which is absent in the stratosphere as well as in deep space. This gives us the opportunity of using stratospheric observation to assess the potential damage to materials in deep space. On the other hand, the deep space environment contains no oxygen while the stratospheric conditions include a low pressure of oxygen. This combination of space factors in stratospheric flight gives us the freedom to separately consider the damaging processes in polymer materials caused by different factors. An additional advantage of the stratospheric flight experiments is low cost, which is very important for modern space programs.

Exposure in space is expected to impact strongly on polymer materials due to the combined effects of low atmospheric pressure, cosmic rays, high intensity UV radiation including short wavelength UV, diurnal temperature variations and other effects associated with solar irradiation on the chemical processes in polymeric materials. Since this combination of conditions cannot be adequately simulated in the laboratory, it is difficult to predict the impact. Such knowledge is particularly important in the

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development of polymers for long term structural applications in deep space, such as the polyethylene sheets proposed to shield high energy cosmic radiation during long term space flights such as the Mars mission [1,2].

Polyethylene film impregnated with Zylon fibres is used for the shell of the stratospheric balloon [3,4]. The mechanical properties of the polyethylene shell satisfy the requirements of balloon deployment and stability in stratosphere [5–8]. For long duration flights the polyethylene film will be exposed under stratospheric conditions for some months. Long-term flights require high structural strength combined with minimal mass. The optimisation of strength/mass requires prediction of the destruction processes in a polyethylene shell for a range of the stratospheric conditions.

The effect of the LEO environment on the polyethylene has been investigated in space and in a simulated free space environment [9–11]. The main effect is an erosion in space of the polyethylene film due to a flux of atomic oxygen with ~5 eV kinetic energy. The rate of etching for high-density polyethylene (HDPE) is 3.5–3.7 × 10^{-24} cm^3/atom. A second effect is oxidation of the surface layer by atomic oxygen. Other effects of high-energy space irradiation on polyethylene were not detectable due to their relatively low intensity.

Destruction of different polymers in free space has been intensively studied, in experiments outside a space ship on LEO and in laboratory experiments [for example [12–19]]. These studies showed that destruction of epoxy composites, HDPE, LDPE, Kapton, Teflon and FEP Teflon, Tedlar, Mylar, fluorinated polyimides, polyurethanes, polysulfone and others during flight on low Earth orbit is primarily due to atomic oxygen bombardment [20]. The results are loss of mass, dehydration processes, the formation of an amorphous carbon layer, the formation of cracks and craters on the surface, and a decrease in the durability of the polymer.

The influence of individual space factors on polymers has been studied in more detail in laboratory experiments. The atomic oxygen, electron and ion fluxes, and the UV light intensity depend on the sun's activity and space ship mission conditions. The NASA database [21] can be consulted to identify space orbit conditions for laboratory simulation. Usually, plasma discharges, ion and atomic beams, and UV light from Krypton, Xenon, Mercury and Hydrogen lamps are used for simulating the space environment in a laboratory. However, no single method provides complete agreement on the effect of space irradiation in simulated and real space environments.

Polymer degradation after exposure in real and simulated free space environment has been observed by optical, electron and atomic force microscopies as an increase in surface roughness; by XPS and FTIR spectroscopy as oxidation of surface layer; by mechanical and thermo-mechanical methods as a decrease in the strength and an increase in the Young's modulus and the glass transition temperature [22–30]. There does not appear to be, however, any detailed investigation of the effects of stratospheric conditions on polymer materials. This paper reports an investigation of the effect of the stratospheric environment on polymer materials compared with that in a laboratory simulated environment. This will facilitate better prediction of polymer behaviour for future stratospheric missions and give a better understanding of the polymer degradation processes under free space conditions.

2. Experiment

2.1. Stratospheric flight

This flight experiment was a part of the NASA scientific balloon flight program realised at the NASA stratospheric balloon station in Alice Springs, Australia. A flight cassette with the polymer samples was installed on the 1200 kg payload carrying the telescope of the Tracking and Imaging Gamma-Ray Experiment (TIGRE). The payload was lifted with a "zero-pressure" helium filled stratospheric balloon of diameter 300 m. The Columbia Scientific Balloon Facility (CSBF) provided the launch, flight telemetry and landing of the payload.

Three cassettes with polymer samples were prepared (Fig. 1). The cassette consists of an aluminium base covered with paint filled with ZnO particles (Dulux, Australia). The first data logger with temperature sensor and microprocessor data storage unit (EL-USB-1, model 23039-50, USA) was placed in an aluminium cylinder, sealed with aluminium disks and glued hermetically with Araldite epoxy resin. The second data logger was placed under the base in the black sleeve. The complete description of the cassette is presented in Ref. [31]. The top of the cassette was covered with two layers of LDPE films of 0.05 mm thickness and 10 × 10 cm^2 area purchased from Goodfellow (UK). The films were stretched and fixed with 6 stainless steel screws. The gap between films was not regulated, but some space between films and between second film and base was clearly observed. A ground control cassette was prepared at the same time with the same samples as the flight cassette. A third cassette was prepared and kept in a refrigerator at +2 to 3 °C all the time.

The flight cassette was fixed on the payload to the GPS antenna bar and moved out to the airstrip. The balloon was launched from Alice Springs Seven Mile airport, Northern Territory, Australia, on the 16 April 2010, at 9:00 am. After 2 h the balloon had risen to 40 km altitude.

Over the next three days the altitude of the balloon varied between 40 km (day time) and 35 km (night time). The geographical coordinates of the balloon, its altitude, the pressure, the temperature and the signal from the video camera were monitored with

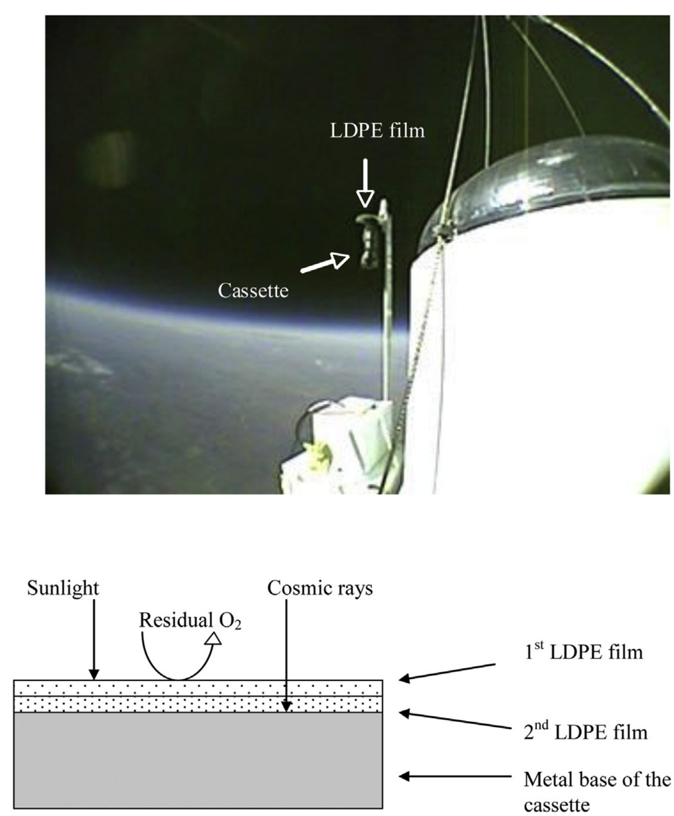

Fig. 1. A telemetry screenshot showing the payload during the stratospheric flight at an altitude of 40 km. The LDPE samples are fixed on top of the cassette.