

Radiation Shielding for Space Exploration: the MoMa – COUNT Programme

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ABSTRACT

In the frame of the multi-disciplinary programme MoMa-COUNT [2], multi-functional protections for human space exploration are being investigated, paying particular attention to flexible materials, selected also for their single excellent structural, thermal and other environmental performances.

These flexible materials in general have poorly known space radiation properties, whose lack of characterisation propagates the uncertainty about the shielding efficiency against the radiation environment on the whole spacecraft protection means. The consequent evaluation of their shielding efficiency, as well as of that of the overall shields, is based on flight experiments performed in Low Earth Orbit (LEO), onboard the International Space Station (ISS) and the re-entry capsule Foton. In parallel, supporting dedicated ground experiments in accelerators, as well as Monte Carlo simulations, are performed.

This paper aims at presenting the more recent activities and results in this field, on the background of the past flight and ground experiments already reported in [1].

INTRODUCTION

The programme MoMa-COUNT ("From Molecules to Man" - COUNTERmeasures) [2] includes, within its aims, the evaluation of passive shielding materials, when

exposed to the natural radiation environments encountered by spacecrafts, made by mixes of trapped particles, solar and cosmic rays. Passive shields are conceived as multi-functional protections including flexible materials whose radiation protection properties are scarcely defined. It is therefore necessary to ascertain both their "absolute" features (radiation transport / interaction properties when each material is considered alone) and the behaviour of composites where some of these materials are present together with other materials, in a sequence dictated by fulfilment of structural, thermal, pneumatic (air-tight) and other environmental (among which: radiation shielding) requirements, with the ultimate goal of mitigating the astronauts' health risks induced by the radiation environment itself [6].

Data on the ISS LEO environment and performances of the shielding materials in that context were obtained [1] as part of:

ESCHILO ("Esperimento di SCHermatura In Low Orbit - Shielding Experiment in Low Orbit") during the ENEIDE mission;

ALTCRISS (Alteino Long Term monitoring Cosmic Ray on the International Space Station), the long duration campaign for measuring the effect of shielding against cosmic radiation in different locations and orientations of the Space Station;

SOFOCLE ("Shielding Options FOr Crew in Low Earth orbit"), long term experiment aimed at evaluating the

effect of shielding tiles fitted on a “poncho” on the anthropomorphic phantom Matroshka.

Additional results on the radiation environment have been obtained in September 2007 with the experiment PARIDE (PARTicle & Ion Dosimetry Experiment) onboard the 12-day long mission of the unmanned spacecraft Foton.

Ground laboratory experiments in accelerators were performed on mono-layers of different materials and thicknesses as well as on composite structures, at the Chiba accelerator (Japan), with 80 and 290 MeV/nucleon Carbon ions, 200 and 500 MeV/nucleon Iron ions [1] and at the Brookhaven National Laboratory (USA) using 1 GeV protons and 1 GeV/nucleon Iron and Titanium ions as proxy to galactic nuclei.

The shielding performances obtained from flight and from ground laboratory experiments were compared and found to be in substantial agreement with the results of a series of Monte Carlo simulations performed with FLUKA and GEANT4 computer codes.

TAS-I ACTIVITIES IN MOMA-COUNT PROGRAMME

The countermeasures foreseen in the multi-disciplinary programme of MoMa-COUNT – an Italian Space Agency (ASI) funded project, conducted in cooperation with the University of Napoli “Federico II” and other academic partners – can be considered of two principal kinds: physical and bio-medical ones [2].

The activities assigned to Thales Alenia Space - Italia (TAS-I) consist in the definition and provision of materials to be tested and studied, with the goal of designing passive radiation shielding means which can act as effective physical countermeasures against radiations for interplanetary vehicles and surface habitat design concepts. These concepts are to be validated, as said, not only by means of tests, both on ground, under particle accelerator beams, and in the true space environment, but, also, via analytical simulations.

It is important to note, in fact, that, during space flight missions, humans, devices and structures have to face the full radiations environment in terms of all particle kinds and entire energy spectra. On the other hand, during ground tests, samples are submitted to particle accelerator beams usually characterised by unidirectional flows of monochromatic, single kind particles, which cannot be fully representative, as such, of the radiation environment present in space. A direct correlation between ground tests and flight tests looks therefore difficult. The missing link can be found in simulations, which can be performed by means of applicative programmes as, for instance, FLUKA and GEANT4. The simulations goal is to obtain the necessary know how so as to perform effective and reliable predictions, with the goal of reasonably

predicting the actual flight behaviour of newly conceived shields.

GROUND TESTS

These tests were performed at the Brookhaven National Lab, within the NASA Space Radiation Lab facility.

A first series of tests aimed at characterising radiation shielding candidate materials, by investigating the total energy released the radiation inside a defined thickness of them, so as, ultimately, to measure its Linear Energy Transfer (LET) and the surface density required to completely stop the incident radiation beam (the radiation range). The materials provided by TAS-I were chosen among the materials largely used in aerospace applications, like: polyethylene, Nextel, Kevlar and aluminium, using as selective criterion that hydrogen and materials rich of hydrogen, or light atoms like carbon, tend to act as efficient radiation shielding.

The performed experiments confirmed the criterion used, and made clear that Polyethylene and Kevlar are actually effective materials to be used as radiation shield, and permitted the identification of the materials LET curve (and its Bragg peak) related to different types of radiation [7]. Figure 1 shows the LET curves obtained irradiating different materials with a 1 GeV/nucleon ^{56}Fe beam: Nextel is the worst performing material, while Kevlar is better being its Bragg peak position and the LET curve closer to polyethylene ones [7].

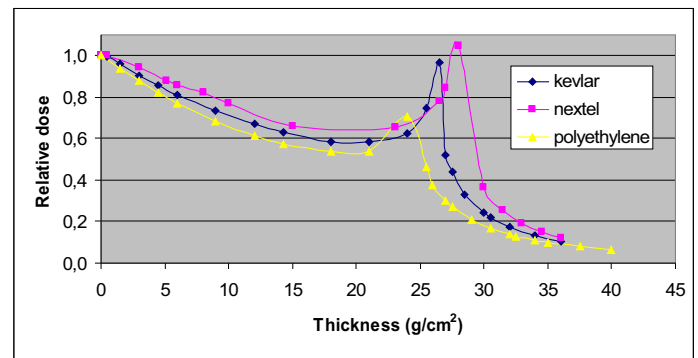


Figure 1: LET curve and Bragg peak for different materials irradiated with 1 GeV/nucleon ^{56}Fe beam

Another set of experiments aimed at investigating the behaviour of different materials (configured as mono- and multi-layers) under a radiation beam and measuring with ionisation chambers the radiation dose delivered before and after them. The tests were performed by means of a 1 GeV/nucleon ^{56}Fe ions beam and 1 GeV protons beam selected with the intent to represent significant components of the Galactic Cosmic Rays (GCR). Samples of targets with different materials, provided by TAS-I, were tested: the “Columbus” multilayer target with and without a modelled equivalent of the internal out-fittings (see below), the “REMSIM” multilayer target (see below), also with an additional water “layer”, Aluminium and Polyethylene layers alone,

of variable thicknesses, and combinations of Aluminium and Polyethylene layers, with mutual positions changed.

“COLUMBUS” TARGET

The rigid multi-layer target labelled “Columbus”, shown by Figure 2, mimics the actual configuration of the Columbus pressurised module external shell, representing the materials employed in the flight model and their areal density, while the transversal distances from one layer to another are not conserved. This structure was studied to protect astronauts from micro-meteoroids and debris impacts and to guarantee a shelter from LEO radiations to the habitable volume inside the module.

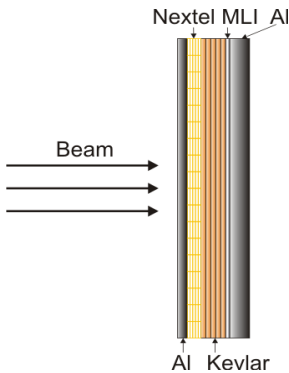


Figure 2: Schematic configuration layout of the rigid multi-layer “Columbus” target

This configuration is composed, as shown in Figure 2, by an external aluminium layer followed by Nextel, Kevlar-Epoxy and MLI and again aluminium, the latter representing the pressurised shell. Inside the pressure shell, the actual habitable volume of the Columbus module is surrounded by a great amount of devices and structures. These objects are composed for the great part by aluminium and composite materials, thus providing a further barrier to radiation. Therefore, these internal out-fittings were modelled, to a certain extent, as additional internal layers, by assessment of a suitable equivalent density of their materials, as far as their role in the interaction with radiation is to be considered. Figure 3 sketches this type of configuration.

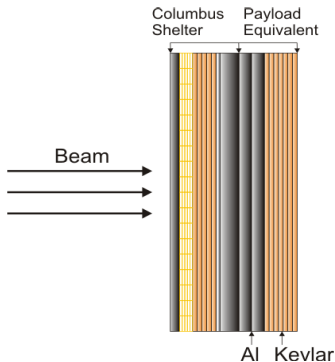


Figure 3: Schematic configuration layout of the rigid multi-layer “Columbus” target with Internal Out-Fitting added layers

Table 1 reports the materials utilised in the “Columbus” multi-layer target without and with the Internal additional Out-Fitting, and the thickness and areal density of each element.

Material	Configuration	Thickness [cm]	Areal Density [g/cm ²]
Al	“Columbus”	0.25	0.7
Nextel		0.55	0.4
Kevlar-Epoxy		0.8	0.9
MLI		0.13	0.2
Al		0.48	1.3
Total “Columbus”		2.2	3.5
Al	Internal Out-fitting	2.8	7.4
Kevlar-Epoxy	Equivalent	2.9	3.8
Total “Columbus” plus Internal Out-fitting Equivalent		7.9	14.7

Table 1: Materials, thicknesses and areal densities for “Columbus” multilayer target with and without the Internal Out-fitting Equivalent

“REMSIM” TARGET

This configuration refers to the multi-layer target selected during the REMSIM study [5], and tested in laboratory with ballistic experiments and subject of simulations with a Monte Carlo code to evaluate its radiation shielding characteristics. Three main parts characterised the flexible multi-layer “REMSIM” target: bumper layers, restraints, air confinement layers.

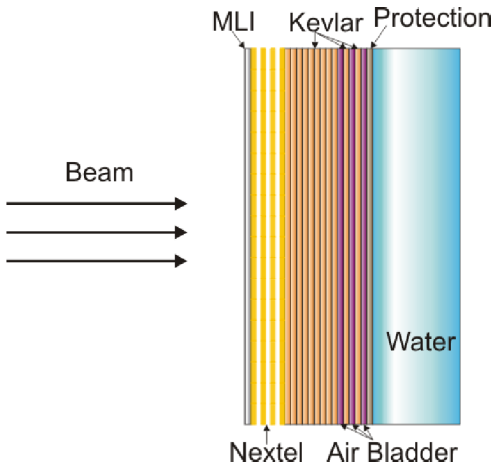


Figure 4: Schematic configuration layout of flexible multi-layer “REMSIM” target

In particular, the tested flexible multi-layer “REMSIM” target, shown in Figure 4, consists of a thermal Multi-

Layer Insulation (MLI), four Nextel layers, ballistic and structural restraint Kevlar multi-layer, then a pneumatic multi layer (airtight bladder) and, eventually, the protective Nomex layer. Some (foam) spacer elements of the flight configuration between some consecutive layers were not used during the radiation tests.

In order to enhance the radiation shielding characteristics of the flexible multi-layer REMSIM type configuration, a water volume, contained inside 2 plastic flasks, 3.7 cm thick each, was added after the puncture/fire protection layer, as representative of the different fluids that will be certainly on board the future exploration modules. (On the contrary other less predictable "solid" configuration elements were not modelled). The areal density added by water flasks to the "REMSIM" target was 7.6 g/cm² (6.9 g/cm² of water and 0.7 g/cm² of flasks plastic).

"REMSIM" layers number and thicknesses are reported in Table 2.

Material	Layers [#]	Total Thickness [cm]	Areal Density [g/cm ²]
MLI + Betacloth	21	0.15	0.04
Nextel	4	0.55	0.40
Kevlar	17	0.45	0.35
Air Bladder	3	0.04	0.05
Nomex	1	0.01	0.014
Total "REMSIM"		1.1	1
Water flasks	2	7.4	7.6
Total "REMSIM" plus additional Water		8.5	8.6

Table 2: Materials for Flexible multi-layer "REMSIM" target

ALUMINIUM AND POLYETHYLENE TARGETS

Space structures make a massive usage of aluminium, thus, some tests focused on evaluating the effects of combining it with polyethylene and to study the behaviour of such multi-layers under radiation.

Materials and configurations tested with 1 GeV/nucleon ⁵⁶Fe ions beam are listed in Table 3, while Table 4 lists materials and configurations tested with 1 GeV proton beam.

Material	Total Areal Density [g/cm ²]
Aluminium	3.5
Aluminium	7
Aluminium	15
Polyethylene	3.5
Polyethylene	7
Polyethylene	15

Table 3: Materials and configurations tested with 1 GeV/nucleon ⁵⁶Fe ions beam

Material	Total Areal Density [g/cm ²]
Aluminium	7
Polyethylene	7
Aluminium	15
Polyethylene	15
5 [g/cm ²] Aluminium + 5 [g/cm ²] Polyethylene	10
5 [g/cm ²] Polyethylene + 5 [g/cm ²] Aluminium	10
10 [g/cm ²] Aluminium + 10 [g/cm ²] Polyethylene	20
10 [g/cm ²] Polyethylene + 10 [g/cm ²] Aluminium	20

Table 4: Materials and configurations tested with 1 GeV proton beam

RESULTS

1 GeV/nucleon ⁵⁶Fe beam tests

This section deals with the results of tests performed with a 1 GeV/n particle beam representative of the heavy-ion component of the Galactic Cosmic Rays (GCR). Highly energetic GCRs can penetrate many g/cm² of matter. During the test campaign an (exactly) 964.9 GeV/nucleon ⁵⁶Fe²⁶ beam was used, with a stopping range in aluminium of 12.6 cm, or 34 g/cm². Three parallel plate ionisation chambers were used as beam monitors, and the dose in different positions was measured by a Far West thimble chamber, the so called egg chamber. Details of the dosimetry at NSRL are described in the reference [4].

The delivered dose was measured positioning the egg chamber centre at 0.3 cm after the sample. Dose reduction data were derived from the dose values normalised with the unshielded dose. Figure 5 lists the results, showing that the Columbus configuration behaves better than an equivalent areal density of aluminium with ⁵⁶Fe ions.