SPACE ENVIRONMENT CHARACTERISATION OF KEVLAR®: GOOD FOR BULLETS, DEBRIS AND RADIATION TOO

R. Destefanis[(1)], E. Amerio[(2)], M. Briccarello[(1)], M. Belluco[(2)], M. Faraud[(1)], E. Tracino[(1)], C. Lobascio[(1)]

[(1)] TAS-I - Thales Alenia Space - Italia S.p.A., Strada Antica di Collegno, 253 – 10146 Torino (Italy)
e-mail: Roberto.Destefanis@thalesaleniaspace.com
[(2)] Sofiter System Engineering, Torino, Italy
e-mail: Ezio.Amerio@sofiter.it

ABSTRACT

Kevlar® is a material extensively used for the design and manufacturing of the shields protecting the manned elements of the International Space Station (ISS) from the threat posed by meteoroids and space debris that increasingly pollute the Earth orbits. Kevlar has been also selected for extensive use in the manufacturing of innovative flexible structures under development for future manned exploration missions. Kevlar initial selection was due to its excellent ballistic properties for debris shielding, but its compatibility with the space environment had to be thoroughly assessed. In parallel to hypervelocity impact tests, to quantify its capabilities to reduce space debris lethality, a significant amount of analysis, testing and simulations was performed to understand and characterise the behaviour of Kevlar in space environment conditions. Structural capabilities, behaviour under thermal cycling, flammability, and outgassing properties have been measured in laboratory for a range of different aramid fabric weavings and composites. More recently, with the aim of developing multi-function protecting structures, the capabilities of Kevlar to protect the human crews from the powerful mix of highly energetic charged particles envisaged during long duration missions have been investigated.
Quite often, in a real project, a systematic selection of materials with appropriate parallel consideration and ranking of all the requirements is not always feasible. Typically, the suitability of a specific material is quickly assessed to ascertain that no show-stoppers exists, based on heritage from past projects, similarity approaches, quickly available screening data. The present paper aims at presenting the Thales Alenia Space-Italia experience with the Kevlar selection process, together with a few results of the characterisation tests performed, focusing on hypervelocity debris impact tests, radiation shielding experiments in accelerator and high vacuum outgassing tests.

1. INTRODUCTION

Kevlar® aramid fibre was initially used by TAS-I, in addition to aluminium and ceramic materials, for the debris shielding systems of the European permanently manned laboratory Columbus, in order to cope with the very severe protection requirements vis-à-vis the threat posed by meteoroids and man made space debris to the crew of the International Space Station [1].
Based on the Columbus heritage, a similar Meteoroids and Debris Protection System (MDPS) was used for the ISS interconnecting elements Node2 and Node3. For other projects, as the Automated Transfer Vehicle Integrated Cargo Carrier (ATV-ICC) and the Cupola, debris shielding concepts making use of Kevlar as intermediate shield were developed [2]. In the last few years, analytical and testing activities have been performed to investigate shielding configurations for inflatable space modules, currently under study for future exploration missions. Needless to say, Kevlar was selected as a key material for these innovative flexible structures.
To evaluate the debris shielding capabilities of Kevlar, and to devise the best shielding configurations, a significant number of hypervelocity impact (HVI) tests have been performed in the last 15 years by TAS-I using the Light Gas Guns (LGG) available at the Fraunhofer-Institut für Kurzzeitdynamik – Ernst Mach Institut (EMI), Freiburg, and at the Center of Studies and Activities for Space (CISAS) – University of Padova ([3], [4], [5]). Several configurations, with flexible Kevlar dry fabric and with Kevlar impregnated with epoxy resin stiff panels, were tested to evaluate their response under a range of conditions simulating debris impacts in the ISS orbit. The Kevlar layer was .placed as intermediate bumper between external and internal shields made from other materials as aluminium, ceramic fibre, metallic and polymeric foams.
To assess the Kevlar compatibility with the space environment in Low Earth Orbit (LEO) operative conditions, structural capabilities (tensile strength, abrasion resistance and tearing strength) coupled with the behaviour under thermal cycling and other properties as flammability and outgassing were measured in dedicated test for selected aramid materials. For the debris shields under consideration, Kevlar is not directly exposed to the space environment and therefore it is not significantly affected by non-penetrating UV radiation or by Atomic Oxygen. On the other hand, its behaviour vis-à-vis vacuum and penetrating particle radiation had to be evaluated. In particular, kinetic

outgassing tests have been performed in high vacuum to evaluate the outgassing-rate and hence to assess the contamination potential of several types of Kevlar fabrics in a variety of operative conditions. In selected tests, in situ mass spectrometer measurement data were acquired to support the identification of the outgassed species.

The capabilities of Kevlar to shield the human crews also from the highly energetic charged particles envisaged during space missions have been characterized, both to evaluate the radiation shielding capabilities of the existing Meteoroids and Debris Protection Shields of several elements of the ISS and to develop multi-function protecting structures (i.e., new integrated radiation and debris shielding systems) for future exploration missions. Ground-based characterisation of the radiation shielding properties of Kevlar (alone and in combination with the other materials used also for debris shielding) was performed, exposing the target materials to high-energy protons and heavy ions accelerated at the NASA Space Radiation Laboratory (NSRL) - Brookhaven National Laboratory (BNL), in cooperation with the University of Napoli "Federico II" [6].

2. TYPICAL KEVLAR PROPERTIES

Kevlar (poly(p-phenylene terephthalamide) - PPTA) is an organic fiber (patented by DuPont) in aromatic polyamide family designated as aramid fibres. The important properties of this class of polymers include thermal and chemical stability and the potential for high melting points, high strength and modulus. These properties derive from the aromatic character of the polymer backbone that can provide high chain rigidity. The percent composition by mass is C (77.06%), H (4.59%), N (12.84%), and O (14.68%). The composition by number is C (50%), H (35%), N (7%), and O (7%). Most applications are based on forms of the polymer that can be prepared as wet spinning and dry spinning of fibers and solution casting of films. Commercially, fibers are available in a variety of forms, including continuous filament yarns of different deniers (or tex numbers). In order to reduce breakage of the yarn during the weaving, a sizing agent on the yarn is applied (usually a silicon-based polymer). With sizing the abrasion resistance of the yarn improves and the hairiness of yarn decreases. After the weaving process the fabric could be "desized" (washed scoured) especially for the application in composite materials and in aerospace fields. A woven fabric consists of two mutually orthogonal families of yarns which can be interlaced in several different styles.

Kevlar K29, K129 and KM2 are very high strength, high toughness forms of Kevlar designed for improved ballistic fragmentation resistance and energy absorption capacity. Table 1 compares single-yarn mechanical properties of the ballistic forms of Kevlar to those of other forms typically used for structural applications (K49, K149). All the forms listed are composed of the same monomer; property difference is due to changes in process conditions which promote additional crystallinity in the high modulus and ultra modulus. These forms of Kevlar differ in the degree of crystallinity, which reflects the degree of molecular alignment and hydrogen bonding between neighboring molecules. In Table 1, E_y is the yarn stiffness, or slope of a quasi-static, tensile stress-strain curve; $\sigma_{y,fail}$ is the yarn *strength*, or maximum stress attained on a tensile stress-strain curve and $e_{y,fail}$ is the strain corresponding to maximum stress. The ballistic forms of Kevlar, and in particular the KM2, are distinguished by relatively large values for both $\sigma_{y,fail}$ and $e_{y,fail}$, which translates into a large value for toughness, or work per unit volume at failure.

Kevlar products provide high temperature durability, low flammability, inherent dielectric strength and excellent chemical resistance, combined with high tensile strength and modulus. These products are well suited to fabrics for protective clothing, paper in electrical uses, and high temperature filtration applications.

Table 1: Kevlar typical tensile properties.

Yarn Type	E_y**(GPa)**	$\sigma_{y,fail}$**(GPa)**	$e_{y,fail}$
Kevlar49	112-135	2.9-3.6	0.024-0.028
Kevlar149	143-175	2.3-3.4	0.015-0.018
Kevlar29	70	2.9	0.036
Kevlar129	88-99	3.4-4.2	0.033
KM2	63-112	3.0-3.3	0.024-0.04

3. DEBRIS SHIELDS FOR MANNED MODULES

3.1 Columbus laboratory

As for the shields developed by NASA for the American modules attached to the ISS [7], Kevlar was selected as an additional layer to improve the resistance of the Columbus debris shields against the small debris, travelling at velocities in excess of 10 km/s in LEO polluted orbits. As shown in Fig. 1, the Columbus "Stuffed" Whipple Shields (SWS) are composed of a Whipple Shield (WS), made from a 2.5 mm thick Al 6061-T6 external sheet, plus an intermediate bumper ("stuffing") made from Nextel fabric and of Kevlar fabric composed with Epoxy resin. The bumper shields protect the primary structure (i.e., the pressure shell, which guarantees an internal habitable volume for the astronauts) made from 4.8 mm thick Al 2219-T851 (BW). Thermal insulations were attached underneath the Kevlar-Epoxy layer or above the pressure shell according to the areas. The MLI were included only in few hypervelocity impact tests, but in all of the radiation shielding tests (see next paragraph). Inside the pressure shell, the actual habitable volume of the Columbus module is surrounded by a great amount of devices and structures, composed for the great part by aluminium and composite materials. These materials have no influence on the resistance of the structure to space debris impacts, where the critical failure is given by penetration of the pressure shell with leakage of the internal atmosphere. On the other hand, these internal out-fittings do provide a significant further barrier to particle radiations and were therefore added for radiation testing (see next paragraph). Table 2 lists the Columbus structure characteristics, including an equivalent amount of the internal out-fitting materials.

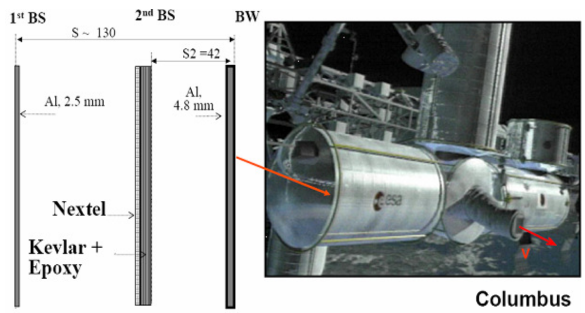

Fig. 1: Layout of the Columbus debris shield configuration

Table 2: Materials data for the Columbus structure (with and without Internal Out-fitting equivalent).

Layer	Material	Area Density [g/cm²]
External Bumper (WS)	Al 6061-T6, 2.5 mm	0.7
Intermediate Bumper (Stuffing)	Nextel 312 AF-62, 4 layers;	0.4
	Kevlar 129 Style 812 18 plies Epoxy resin Brochier 914	0.9
Thermal insulation	MLI	0.2
Back Wall (BW)	Al 2219-T851, 4.8 mm	1.3
Total Columbus SWS (~2.2 cm thick)		**3.5**
Internal Out-fitting Equivalent	Al 2219-T851, 2.8 mm	7.4
	Kevlar-Epoxy	3.8
Total Columbus SWS plus Internal Out-fitting Equivalent (~7.9 cm thick)		**14.7**

A significant number of hypervelocity impact tests using the Light Gas Gun of the Ernst Mach Institut was performed on the Columbus configuration during the design development activity, performed from 1995 to 1998 ([8], [9]). Aluminum alloy spherical projectiles were fired at velocities between 3 and 7 km/s with impact angles between 0 and 60 degrees. The LGG tests showed very good ballistic performance: at high velocity (around 6.5 km/s) normal and 45º obliquity impacts: the Columbus SWS was able to resist (without perforation or leak of the pressure shell) to impacts with masses above 4.5 g (i.e., with diameters > 1.45 cm). The ballistic limit at low (around 3 km/s) and at medium (around 5 km/s) velocity was in the same mass range. For 60º impacts, even very massive projectiles (above 8 g, 1.75 cm in diameter) could not penetrate the structure in the complete velocity range. A Columbus impacted target is depicted in Fig. 2.

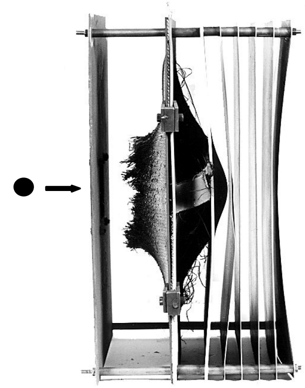

Fig. 2: Columbus SWS target impacted by a 15 mm (5 g) Al sphere at 6.51 km/s (test #8611, failed)

The analysis of the test results, showed the response of the Columbus 3-wall system to hypervelocity impacts to be rather complex: in the experimental range the damage on the BW did not increase linearly with the impact velocity and angle, but showed non-monotonic variations. The Nextel/Kevlar stuffing was shown to have excellent capabilities in absorbing the impulsive load of the debris cloud generated by the projectile impact on the external Whipple Shield. When solid fragments reached the rear wall, the pressure shell failed (with cracks propagation) for much lower impact energy. Also in these cases, the Kevlar stuffing was very effective in reducing the lethality of the projectile residual solid fragments responsible for the initiation of the target failure process. Thanks to the protection provided by the debris shields with Kevlar, the Columbus module and the Nodes are capable to resist the polluted debris environment in the ISS orbit with a mean time between critical failures (penetration) in the order of 900÷1000 years.

3.2 ATV-ICC cargo carrier

Kevlar is also extensively used for the ATV, the European cargo spaceship that will deliver experimental equipment and spare parts as well as food, air and water to the ISS. The structural configuration of the ATV-Integrated Cargo Carrier (which is the pressurised section that allows the astronauts dressed in regular clothing to access its contents during its joint orbital flight with ISS) is shown in Fig. 3, together with the picture of a test sample of the same configuration used for HVI tests. The configuration was composed of an external Whipple Shield made from Al 5083,1.2 mm thick, with area density (AD) of 0.315 g/cm^2, a back wall (BW) made from Al 2219-T851, 3.0 mm thick, with AD 0.852 g/cm^2. To optimize the design, the thermal passive system, i.e., the Multi-layer insulation (MLI) was placed on top of the Aluminium external bumper panels. The MLI was composed of 18 layers of Double Aluminized Mylar, spaced by Dacron-net, with an external β-cloth (Teflon-coated fibre-glass woven cloth) layer and an internal Double Aluminized Kapton layer. A stuffing made from 2 layers of ceramic fabric Nextel 312 AF-10, 3 layers of Kevlar KM2 SEAL364 wrapped with Single Aluminized Kapton (with an AD of only 0.13 g/cm^2) was added as intermediate layer. The overall area density of the structure was approximately 1.4 g/cm^2.

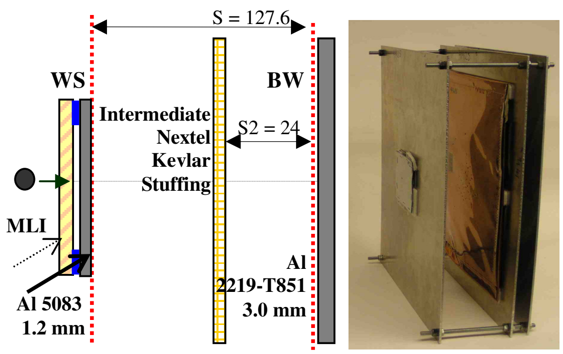

Fig. 3: Layout of the ATV ICC test target (all dimensions in mm) and actual target before test.

Hypervelocity impact tests using two-stage LGG at EMI were performed firing aluminium spheres to simulate space debris with diameters between 2.3 and 9.0 mm (0.02 and 1.07 g) at velocities comprised between 2.9 and 7.2 km/s, and with impact angles of 0, 45 and 65 degrees. Initial test were performed without the intermediate Nextel/Kevlar stuffing layers. The tests results showed the MLI on top of the bumper shield to have an unexpectedly strong adverse influence on the ballistic performances. The ATV-ICC configuration with the β-cloth MLI (but without the Nxtel/Kevlar stuffing) was perforated under normal impact by a 4.5 mm (0.13 g) aluminium sphere at 6.6 km/s. On the other hand, the introduction of the light Nextel/Kevlar intermediate stuffing was sufficient not only to compensate the negative MLI effect, but to improve the final performance of the shield with a moderate mass increase. Very good ballistic performances were obtained for normal impacts both at low and high velocities. The Kevlar stuffed configuration survived normal impacts with diameters as large as 8.5 mm (0.9 g) at 7.15 km/s (with small craters). These good ballistic performances were obtained for normal and oblique impacts both at low and high velocities.

Note that the ATV cargo element is only temporarily attached at the ISS for a period in the range of 6 months, before being disposed of with a targeted re-entry. This justify the shielding lower ballistic resistances with respect to the permanently attached elements (i.e., Columbus, Nodes), with a mean time between critical failures (penetration) of the order of 260 years.

3.3 Flexible structures

The inflatable structures under development at TAS-I for the future manned space missions are multi-layered systems composed of lightweight flexible materials, with integrated synergistic capabilities to protect from the various component of the external environment. Fig. 4 shows an example of a typical inflatable configuration with flexible shields. Four *functional blocks* can be identified*:*

- *Thermal protection* provided by MLI, whit an external layer selected to protect the underlying layers from atomic oxygen erosion and ultra violet degradation
- *MMOD shielding system* (to protect the internal structure which guarantees air and pressure containment) composed of *shock* shields and *energy absorber / ballistic restraint* layers;
- *Pressure containment* provided by a structural restraint, which may be made either from a few continuous fabric layers or of a strap net;
- *Air containment* provided by redundant bladder;
- *Internal barrier,* to provide protection of the outer layers from fire and damages that could be accidentally induced by crew activities;
- *Spacer elements* (not shown in the figure) consist of low density open cell foam blocks and are (discontinuously) inserted to guarantee correct spacing between consecutive bumpers and restraint.

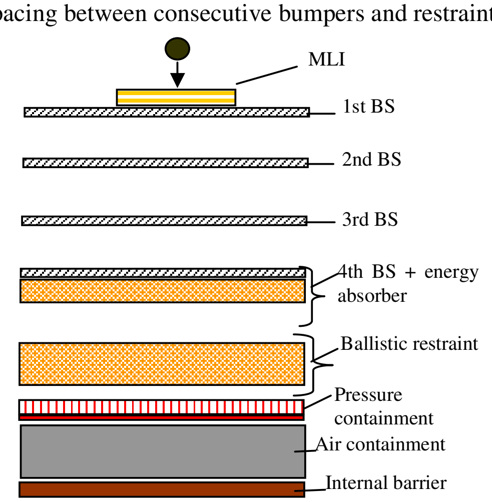

Fig. 4: Typical layout of inflatable structure (REMSIM configuration).

Aramid fabric is used in several functional blocks of the integrated systems, and, in particular, for the shielding, and energy absorbing component, for the pressure load containment and for the innermost internal barrier. The debris shield is based on the *Multi-Shock* shielding concept, using multiple thin layers to repeatedly shock the impacting projectile. The multiple shocks aim at increasing the temperature of the debris cloud up to a complete melting and/or vaporization of the fragments, even at impact velocities that normally do not produce phase transitions when single or double bumper shields are used. Based on this mechanism, different debris shield lay-out are possible, with introduction of energy absorbing layers devoted to simultaneously shock and absorb the impact kinetic energy of the projectile/debris cloud. As in the Columbus and ATV shielding configurations, also in these integrated flexible systems Kevlar shows excellent capability in absorbing the kinetic energy induced by the debris cloud generated by the impacting projectile. Kevlar can also be used as *shock layer*, although the capability of shocking the impacting projectile remains lower than that offered by ceramic fabrics. In current development, Kevlar is also used as structural restraint: a *strap net* made of a mix of Zylon and Kevlar fibers sewed on a continuous fabric layer of Zylon was shown to assure excellent pressure load carrying capability.

For the configuration shown in Fig. 4, with an overall area density of about 1.0 g/cm^2 and an overall spacing of 30 cm, the critical failure was set as the penetration of the external air containment layer. LGG testing showed the normal impact with a 12 mm diameter aluminum sphere (2.5 g), at 6.7 km/s to be slightly below this failure threshold. Table 3 lists the inflatable structure characteristics, including the internal water tanks that are envisaged on board of the future exploration modules. These water flasks have no influence on the resistance (i.e., critical failure) of the structure to hypervelocity impacts. However, the internal water flasks provide a significant shielding against radiations and were therefore added for radiation testing (see next paragraph). This flexible configuration was named "REMSIM" after the eponymous study [10].

Several shielding configurations for different mission scenarios (short and long duration, in debris polluted LEO or in non-Earth orbits without debris, but only with meteoroids) with low, medium and high ballistic capabilities were investigated in a few HVI test campaigns. Fig. 5 shows an impacted target of a light weight flexible configuration with low-medium ballistic capabilities. With an overall area density of only 0.5 g/cm^2 the target was able to resist an 45º obliquity impact with a 5 mm Al sphere (0.178 g) hitting at 7.13 km/s. Improvements to the REMSIM configuration led also to devise a target with an area density of 1.0 g/cm^2 able to stop 14.5 mm diameter (4.5 g) Al spheres at 45°.

Table 3: Materials data for the REMSIM inflatable configuration (with and without internal water flasks).

No. of Layers	**Material**	**Area Density [g/cm^2]**
21	MLI + Betacloth	0.08
4	Nextel 312 AF-62, 4 layers	0.41
17	Kevlar KM2 fabric	0.36
3	Air containment	0.05
1	Aramid internal barrier	0.01
Total REMSIM (~1.1 cm thick)		**1.0**
2	Water flasks	7.6
Total REMSIM plus additional Water (8.5 cm thick)		**8.6**

Fig. 5: Light flexible impacted by a 5 mm Al sphere at 7.13 km/s, 45º (EMI test #4914). Test passed with minimal damage to the ballistic restraint.

4. CONTAMINATION AND OUTGASSING

Basic outgassing screening tests are usually performed according to the ECSS-Q70-02 or to the ASTM E-595 standards, where a sample of the material being studied is held at a temperature of 125°C for 24 hours at a pressure in the range of 10^{-3} Pa. Typical acceptance criteria are: Total Mass Loss (TML) < 1.0 %, Collected Volatile Condensable Material (CVCM) < 0.1 % and Recovered Mass Loss (RML) < 1.0 %.

Screening test data for generic materials are often available in literature or on online databases, but, quite often, a broad interval of values is reported for the screening data. For instance, for Kevlar 29, the MAPTIS database reports the values range listed in Table 4. A narrower range is addressed in the JAXA Material Database, where the data obtained by JAXA and NASA using the ASTM E595-93 standard are compared (see Table 4). However, precise material data for the specific material selected (and from the exact supplier) are necessary, because small deviation in the manufacturing process, finishing and the surface treatment of the sample (and even its thermal history) may have a significant effects on the outgassing results. Moreover, when the development of the Stuffed Whipple Shield for Columbus started, few information on the Kevlar outgassing properties were available.

Testing according to the ESA PSS-01-702 standard available at that time (125°C for 24 hours, pressure < 7 10^{-3} Pa, collector plate at 25°C) was performed, with the result listed in 0. The tests were performed separately on the fabric selected (Kevlar 129 Style SEAL 812) both with sizing and de-sized (washed). The final composite (i.e., the Kevlar fabric composite with Epoxy resin Brochier 914) was also tested.

Table 4: Kevlar 29 outgassing screening properties .

	TML(%)	CVCM(%)	RML(%)
MAPTIS	0.13 – 4.3	0 – 0.27	0.095 – 3.71
NASA	2.18	0.02	0.41
JAXA	2.02	0.27	0.47

Table 5: Outgassing screening properties of Kevlar 129 used for the Columbus shields.

Material	TML(%)	CVCM(%)	RML(%)
K 129-812 sized	7.74	0.03	1.84
K 129-812 washed	4.78	0.03	1.89
K 129-812 washed + resin 914	2.32	0.00	0.26

Based on these tests, it was decided to proceed with the development of the debris shielding using the Kevlar-Epoxy. The data showed that most of the outgassed product was water vapour, which was expected to be vented in the Shuttle cargo bay during transport to the ISS. This release of water was not expected to be critical due to the absence of surrounding surfaces at cold temperatures close to -100° C. However, since a significant amount of Kevlar-Epoxy is used as part of the Columbus MMOD shields (with an area of approximately 42 m^2 and a mass in the range of 300 kg) precise outgassing rate data were necessary. Therefore, more accurate dynamic outgassing testing was performed at ESA-ESTEC. Long duration tests (435 hours) were performed on Kevlar fabric cured at 180°C with Epoxy resin, with a sample temperature of 135°C, three Quartz Crystal Microbalance (QCM) collectors at -21°C, -47°C, -75°C and a pressure < 10^{-4} Pa. The TML obtained at the end of the test was 2.07%, while the amount of volatile condensable material collected on the QCMs, together with the deposition rate are listed in Table 6. NASA/JSC performed parallel outgassing testing according to ASTM E1559, to derive suitable data for the ISS system level molecular deposition analysis, performed with the NASAN computer code. This analysis relies on a geometrical model of the complete ISS, with the expected on-orbit temperatures and effective condensable outgassing rates. The aim of the analysis was verifying the ISS system level requirement for molecular deposition from all quiescent contamination sources to be lower than 30 Å/year. The outgassing data used by NASA for the Columbus Kevlar-Epoxy are shown in Table 7.

Table 6: Kevlar-Epoxy outgassing data after 435 hrs measured at ESTEC.

Source at -135°C	Volatile condensable material (%)	Condensable Ougassing rate [g/(cm^2•s]
Collector at -21°C	0.011%	1.80E-11
Collector at -47°C	0.011%	1.60E-11
Collector at -74.9°C	0.012%	1.50E-11

Table 7: Kevlar-Epoxy outgassing data after 144 hrs used by NASA.

Source temperature °C	Condensable Ougassing rate [g/(cm^2•s] at Collector temperature °C		
	-75	-25	25
135	1.21E-11	1.16E-11	4.90E-14
110	1.21E-11	1.16E-11	4.90E-14
80	2.89E-12	2.53E-12	8.43E-14

Other outgassing tests were also performed on several types of Kevlar fabric (without Epoxy) for application in other projects. Quite recently testing has been performed on a lot of Kevlar KM2 Style CS705 that was purchased with a water repellant treatment (Zonyl D® water repellant fluorchemical finish). The tests were performed (by OSI, Outgassing Services International) according to the standard ASTM E1559, with a source temperature of 45 °C. This rather low temperature was determined by an integrated thermal analysis considering the precise location of the Kevlar material on the ISS element Node 3. The test duration was 144 hours and the QCM collectors were kept at 80 K, -75°C, -25°C, +25°C. The outgassing rate (OGR) data obtained are listed in Table 8.

After the isothermal outgassing test, a QCM thermogravimetric analysis (QTGA) was performed on the collected outgassed species. The QCM at 80 K was heated at a controlled rate from their base temperatures to 398 K, in order to volatilize the collected species. During this QCM heat-up the mass remaining on the QCM was measured as a function of time and temperature. The QTGA data are plotted in Fig. 6 as evaporation rate from the QCM as a function of QCM temperature. Data from the in situ mass spectrometer were also used to help identify the outgassed species. These data confirmed the hygroscopic behavior of Kevlar: water, with a m/z ratio of 18, was identified as the species with major relative abundance. Other species (phthalates, hydrocarbons various unidentified aromatics) were observed with minor relative abundance. Note that all the species were still detected by the mass spectrometer in the outgassing flux at the end of the test.

Table 8: Kevlar KM2 CS705 WR outgassing data measured at OSI, according to ASTM E1559.

QCM temperature. [°C]	OGR [g/(cm2 s)]	TML [%]	CVCM [%]
-193	4.94E-12	1.78	
-75	5.90E-13		0.00501
-25	6.00E-14		0.00089
25	4.00E-14		0.00049

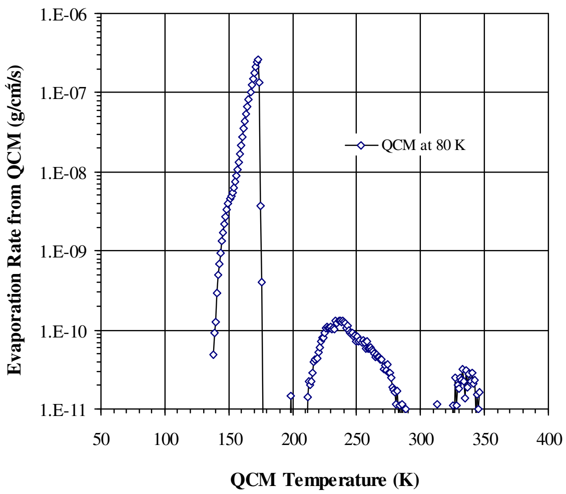

Fig. 6: QCM thermogravimetric analysis on Kevlar KM2 CS705 WR at 45°C.

5. RADIATION SHIELDING

At present, bulk shielding is the only practical countermeasure to protect human crews against space radiation. Basic physics, mathematical models, and both ground-based and flight measurements clearly showed that light, highly hydrogenated materials, as, for instance, polyethylene, provide the best shielding. To assess the poorly known space radiation protection capabilities provided by the materials composing the debris shielding and the inflatable structures, ground tests both with 1 GeV protons and 1 GeV n^{-1} ^{56}Fe ions beams were performed at the Brookhaven National Laboratory (BNL). Kevlar, ceramic fabric (Nextel) and Aluminum composing the debris shields were tested, together with polyethylene, which has excellent shielding properties in space and was therefore tested in the same conditions for comparison.

5.1 Tested configurations

A first series of tests was performed on the separate materials composing the typical debris shields: Nextel, Kevlar, Aluminum and High Density Polyethylene (HDPE, $\rho = 0.97$ g cm^{-3}) to investigate the total energy released inside a defined thickness of the individual materials. Bragg curves of ^{56}Fe-ions with an estimated energy at the sample position of 968 MeV n^{-1} were measured at BNL using a calibrated egg-ionization chamber. The 1 GeV n^{-1} Fe-beam was selected as a useful simulator of the actual galactic cosmic radiation (GCR) heavy ion spectrum ([6], [11]).
Another set of experiments was performed to measure dose reduction induced by selected complete debris shielding configurations, both with 1 GeV protons and 1 GeV n^{-1} ^{56}Fe ions.
The Columbus multilayer targets (with and without a modelled equivalent of the internal out-fittings) used for the radiation tests are shown in Fig. 7. The tested configurations reproduce the configuration used for the Coumbus Stuffed Whipple Shield (with material and area density data listed in Table 2), neglecting only the transversal distances between the various layers.

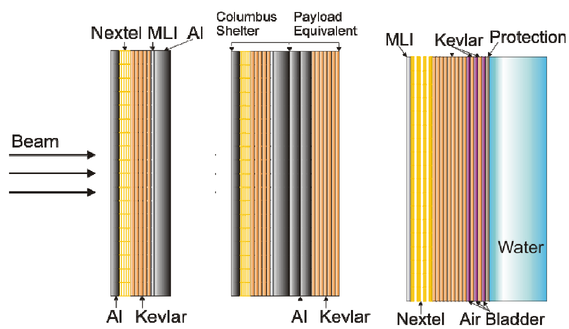

Fig. 7: Schematic configuration layout of: the Columbus target without (left) and with (center) Internal Out-Fitting added; the flexible multi-layer REMSIM target (right).

The tested multi-layer target mimicking a typical multi-layer configuration for inflatable space modules (REMSIM target) is also shown in Fig. 7. This target was composed of a thermal Multi-Layer Insulation (MLI), four Nextel layers, ballistic and structural restraints made from Kevlar fabrics, a pneumatic multi-layer (airtight bladder) and a protective aramid (Nomex) layer. With respect to actual debris shielding configurations, low density foam spacer elements and transversal distances between the various layers were neglected for radiation testing. In order to enhance the radiation shielding characteristics of the flexible multi-layer configuration, a water volume, contained inside two plastic flasks 3.7 cm thick each, was added after the innermost layer, as representative of a possible multi-purpose passive radiation shield. The areal density added by water flasks was 7.6 g/cm^2 (6.9 g/cm^2 of water and 0.7 g/cm^2 of flasks plastic). REMSIM material data and area densities are listed in Table 3.

5.2 <u>Radiation tests results</u>

The Bragg curves measured on the individual materials with the 964.9 GeV n^{-1} $^{56}Fe^{26}$ beam (with a stopping range in Aluminium of 12.6 cm, or 34 g/cm^2) are reported in Fig. 8. Fig. 9 shows – for both individual materials and debris shielding targets - the dose reduction data (for the same ions beams) derived from the dose values measured by a Far West thimble chamber positioned 0.3 cm after the targets and normalised with the unshielded dose.

The Bragg curves show an initial decrease caused by the ions fragmentation, followed by the Bragg peak and by a long tail produced by light fragments. These test data showed Kevlar to be a good radiation shielding material, with an effectiveness close (80-90%) to that of polyethylene. In particular, both the initial decrease in dose induced by Kevlar and the minimum dose before the Bragg peak are rather close to the values obtained for HDPE. These data confirmed that hydrogen-rich materials (i.e., HDPE) are effective radiation shields, but also show that Kevlar, which is rich in light atoms like carbon (~50% in number), is rather effective. Nextel (and Aluminium), on the other hand, resulted to be much poorer radiation shielding materials and the expected reduction on dose was roughly half (and 1/3) of that provided by the same mass of polyethylene. Adding mass after the external shield brings to a remarkable reduction of the delivered dose. For the Columbus configuration, when the out-fittings were added the dose reduction (evaluated at the internal wall surface) jumped from about 10% to about 30% confirming that the equipment and structures inside the module actually contribute to mitigate the radiation effects on astronauts, due to the shift along the LET curve.

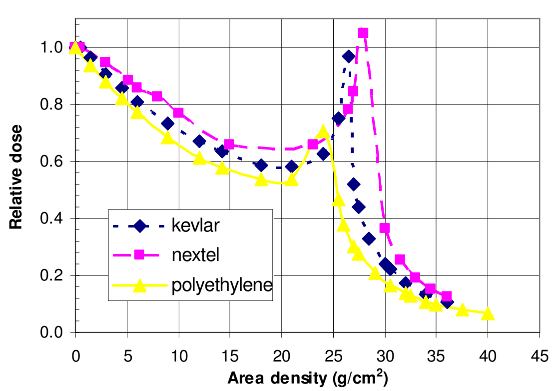

Fig. 8: Bragg curves of 968 MeV n^{-1} ^{56}Fe -ions measured in HDPE, Kevlar and Nextel. Dose is normalized to the value measured without shielding.

Fig. 9 shows also that the Columbus configuration reduces the delivered dose significantly better (from roughly 40% to 90%, with and without outfitting, respectively) than an equivalent areal density of Aluminium. Compared with the HDPE, the Columbus has a relative efficiency in dose reduction lower of about 30% in both cases. Also the REMSIM target (with water) showed a good reduction dose performance, with only a 10% lower efficiency than polyethylene.

The test results obtained with the proton beam at 1 GeV (with a LET in water of about 0.22 KeV/µm) were obtained measuring the dose delivered at different positions (ranging from 0.3 cm to 80 cm) before and after the Columbus and REMSIM targets, by means of the Far West thimble chambers.

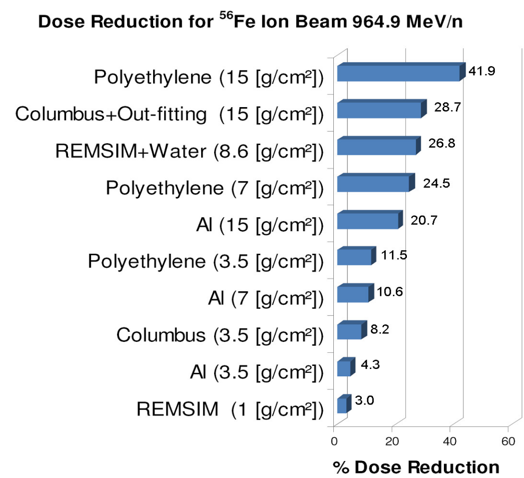

Fig. 9: Dose reduction vs target, obtained irradiating the samples with a 1 GeV $^{n-1}$ ^{56}Fe ions beam, with reference to the unshielded beam dose

Fig. 10 shows the amount of dose (normalised with the dose delivered by the unshielded beam) as a function of the distance, along the 1 GeV proton beam axis for the Columbus plus out-fitting sample. The dose value measured at the sample position (and up to 12 cm uprange) was increased due to the secondary particles, generated by the impinging protons interacting with the shield itself and partly back-scattered. The dose at the internal wall sample position increased by about 25% for the Columbus plus out-fittings target, while it decreased to about 80% of the total dose at a distance of 80 cm from the sample. This decrease is essentially due to the presence of air that contributes to stopping the outcoming particles, and to the limits of the experimental set up that detected only the radiation along the beam axis direction (neglecting its lateral spreading).

Also for the 1 GeV protons, the Columbus structure behaved significantly better in terms of dose reduction than a pure aluminium wall of the same areal density: while for the Columbus (plus out-fittings) target the normalised dose, measured 0.3 cm after the sample was about 1.25, for the 15 g/cm^3 aluminium block, the measured normalised dose (in the same experimental conditions) was about 1.58.

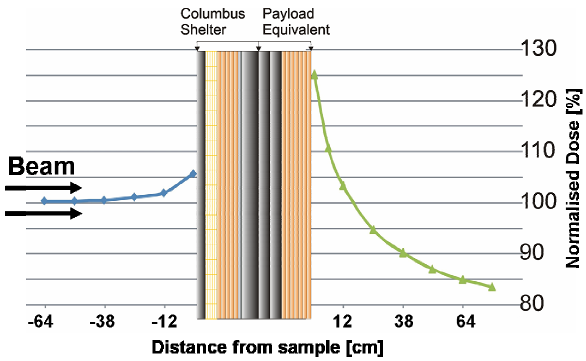

Fig. 10: Relative dose measured as a function of the distance along the proton beam axis for Columbus plus Equipment Equivalent target

Fig. 11 compares the normalized dose as a function of the distance, along the proton beam axis, of the Columbus (plus out-fitting) and for the REMSIM (plus water) targets, showing a similar behaviour when irradiated by the proton beam. Actually the REMSIM (plus water) target presents a slight advantage with respect to the Columbus (plus outfitting), mainly due to the presence of water, in spite of its lighter area density (8.6 versus 14.7 g/cm^2).

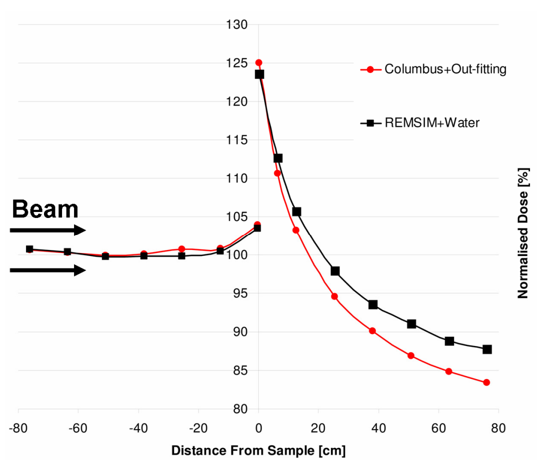

Fig. 11: Relative dose as a function of the distance along the 1 GeV proton axis for the Columbus plus out-fittings and for the REMSIM plus water targets.

6. CONCLUSIONS

The selection of an innovative material for space application is typically driven by its capability to respond to a specific requirement. For non-metallic materials, the compatibility with the various space environment components and in particular with vacuum and thermal cycling must be carefully assessed. Kevlar exceptional ballistic capabilities make it a key material for the shielding systems – existing and under development – devised to protect spacecraft from the threat posed by space debris. Kevlar behavior in space environment, and in particular its outgassing properties, resistance to hypervelocity impacts and particle radiation shielding have been well characterized as individual material and in combination with other materials. The results obtained are used for the design and verification of debris shielding systems, in the frame of several space projects.

7. REFERENCES

[1] Beruto E, Destefanis R and Faraud M., Debris shielding development for the Columbus Orbital Facility, *Second European Conference on Space Debris*, Darmstadt, Germany, ESA SP-393, 1997.

[2] Destefanis R, Lambert M, Scha¨fer F, Drolshagen G, and Francesconi D., Debris shielding development for the ATV Integrated Cargo Carrier, *Fourth European Conference on Space Debris*, Darmstadt, Germany, ESA SP-587, 2005.

[3] Destefanis R and Faraud M., Testing of advanced material for high resistance debris shielding, *Int. J. Impact Engng.,* Vol.**20**, 209 –222, 1997.

[4] Destefanis R, Schäfer F, Lambert M, Faraud M. and Schneider E., Enhanced Space Debris Shields for Manned Spacecraft, *Int. J. Impact Engng*., Vol.**29**, 215-226, 2003.

[5] R. Destefanis, et al., Selecting Materials to Protect Inflatable Structures from the Space Environment, *10th International Symposium on Materials in a Space Environment*, Collioure, 2006.

[6] Lobascio C., et al., Accelerator-based tests of radiation shielding properties of materials used in human space infrastructures, *Health Phys*.;94(3):242-7, March 2008.

[7] Cour-Palais B.G and Crews J.L. A Multi-Shock Concept for Spacecraft Shielding. *Int. J. Impact Engng*., Vol.**10**, 135-146, 1990.

[8] Destefanis R, Faraud M, and Trucchi M., Columbus Debris Shielding Experiments and Ballistic Limit Curves, *Int. J. Impact Engng*., Vol.**23**, 181-192, 1999.

[9] E. Schneider, F. Schäfer, R. Destefanis, M. Lambert, "Advanced Shields for Manned Space Modules", IAC-04-IAA.5.12.2.01, 2004.

[10] Cougnet C., et al., Radiation Exposure and Mission Strategies for Interplanetary Manned Missions (REMSIM), *Earth, Moon and Planets, Special Issue "Human Space Exploration"*, 2005.

[11] Lobascio C., et al., Radiation Shielding for Space Exploration: the MoMa – COUNT Programme, *ICES 2008-024*, 2008.