SIDER Report Summary

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Final Report Summary - SIDER (RADIATION SHIELDING OF COMPOSITE SPACE ENCLOSURES)

Executive Summary:
Composite structures show potential for significant mass savings. Composite constructions can meet the structural constraints set for the traditional aluminium spacecraft electronics housings. To provide adequate thermal energy transfer (thermal conductivity) special carbon fibres can be used. Composite structures also show potential for significant mass savings. Electromagnetic radiation can be handled with electrically conductive coatings or layers. However, radiation protection capabilities of composite structures provide considerable challenges.

Energetic particles, mainly electrons and protons, can destroy or cause malfunctions in spacecraft electronics. Therefore adequate protection for the electronics has to be provided by the electronics housing together with local shields. Space electronic systems employ enclosures to shield sensitive components from space radiation. The purpose of shielding is to attenuate the energy and the flux of ionizing radiation as they pass through the shield material, such that the energy per unit mass (or dose) absorbed in silicon is sufficiently below the maximum dose ratings of electronic components. The standard practice in space hardware is the use of aluminium as both a radiation shield and structural enclosure.

The received radiation amount varies significantly depending on several variables that include mission parameters (orbit, altitude, inclination and duration), spacecraft design (spacecraft wall thickness and panel-enclosure location). To achieve the optimum shielding with the minimum weight, all these variables have to be considered in the design.

Depending on mission altitude and inclination and the dose rating of electronics, the thickness of aluminium necessary for shielding can substantially exceed that required for structural strength, resulting in significant weight penalties. Satellite designers use composite materials which have higher strength-to-weight ratios than aluminium. However, conventional graphite epoxy composites are not as efficient shielding materials as aluminium because of their lower density, that is, for the same mass, composites provide 30 to 40% less radiation attenuation than aluminium. Conversely, for the same radiation attenuation, the composites tend to be 30 to 40% thicker than aluminium.

In SIDER project a technology based on nanomaterials is proposed as an alternative for the radiation shielding. A second strategy based in the incorporation of a high density material foil is also being considered. The adhesion of the foil to the CFRP laminate is an issue to be solved.

Another key aspect for the development of a more effective, lightweight, radiation shielding material is the understanding of the transport phenomenon and the nature of interactions between space radiation and shielding material. Detailed physical simulation of space radiation interaction with satellite structure materials, electronics enclosures and device cases is necessary in order to develop the strategy for an optimal improvement of the shielding properties of the composite structures. The simulations carried out will allow identifying:

- Material to be incorporated to the composite enclosure to obtain the required level of radiation shielding with minimum mass;
- Amount to be incorporated;
- Position in the composite enclosure

Radiation tests have been used to validate the results obtained in the simulations. With a good understanding of the phenomena, it will be possible to predict the level of radiation by using simulation software and avoid expensive testing costs.
and time consuming tests.

The main objective of this project is the development of the technologies and tools required to obtain lightweight, safe, robust and reliable composite structures.

Project Context and Objectives:

Project Concept

Space electronics systems employ enclosures to shield sensitive components from space radiation. The purpose of shielding is to attenuate the energy of charged particles as they pass through the shield material, such that the energy per unit mass (or dose) absorbed in silicon is sufficiently below the maximum dose ratings of electronic components. The standard practice in space hardware is the use of aluminium as both a radiation shield and structural enclosure.

Depending on mission altitude and inclination, and the dose rating of electronics, the thickness of aluminium necessary for shielding can substantially exceed that required for structural strength, resulting in significant weight penalties. Satellite designers use composite materials which have higher strength-to-weight ratios than aluminium. However, conventional graphite epoxy composites are not as efficient shielding materials as aluminium because of their lower density, that is, for the same mass, composites provide 30 to 40% less radiation attenuation than aluminium. Conversely, for the same radiation attenuation, the composites tend to be 30 to 40% thicker than aluminium.

Spacecraft operating in LEO (Low Earth Orbit) and GEO (Geostationary Orbit) orbits is exposed to spatial radiation. The main components of the space environment are energetic electrons and protons. These form the total energy deposition (dose) of a component. Energetic particles passing through material can undergo a variety of interactions leading to energy loss, scattering and/or the generation of secondary particles.

Energetic protons are heavier particles than electrons and normally follow virtually straight paths. Electrons are rather “light” particles which interact with material mainly at the atomic level, producing excitation and ionisation. For electrons of low energy, almost all energy loss on passing through material is attenuated by interaction mechanism that results in ionisation of the material. In addition to energy loss by collision, there is a further contribution to stopping power due to the generation of energetic photons when electrons decelerate in the strong electric fields of the atom. This radiation is called bremsstrahlung (braking radiation).

Shielding against space radiation can be done at several levels: the electronic device level, the enclosure level and the spacecraft structure level. While the spacecraft structure provides some level of attenuation for incoming charged particles, it is usually not enough to provide the required shielding level. The received radiation amount varies significantly depending on several variables that include mission parameters (orbit, altitude, inclination and duration), spacecraft design (spacecraft wall thickness and panel-enclosure location) and the type and sensitivity of semiconductors used. To achieve the optimum shielding with the minimum weight, all these variables have to be considered in the design.

Another key aspect of development of more effective, lightweight, radiation shielding materials is the understanding of the transport phenomenon and the nature of interactions between space radiation and shielding material. Detailed physical simulation of space radiation interaction with satellite structure materials, electronics enclosures, and device cases is necessary in order to develop strategy for optimal improvement of shielding properties of the composite structures. Analysis of space radiation penetration to a given point inside the satellite and effects of space radiation on the sensitive satellite elements is a widely used technology of radiation designing. Implementation of this technology into composite structure development expands their functionality. On the basis of this analysis it will be possible to answer the following questions:

- What substance shall be added to the composite enclosure to obtain required level of radiation shielding with minimum mass loss;
- What amount of the substance shall be added to the composite enclosure;
- Where in the composite enclosure shall be inserted the substance in order to obtain required level of radiation shielding.

Radiation tests are necessary for verification of improvement concepts of the composite enclosure radiation shielding properties. Testing development is necessary to check the validity of the modelling and the analysis. With a very good understanding of the phenomena it will be possible to predict the level of radiation only by using simulation software and avoid expansive testing costs and time consuming tests.
Preliminary studies to understand and simulate the particle attenuation in composite structures have already been performed by Partners of the SIDER Consortium (“Advanced Equipment Design” (AED), “Radiation Protection for Advanced Equipment Design”, “Multifunctional Structures” (MULFUN) projects).

In the MULFUN project, the use of composite materials as housing for electronics and as multifunctional structures was studied. The developments were focused in the integration of the electronics and in the thermal and mechanical behaviour of the structures. In the AED project a radiation attenuation study was performed but the results obtained, especially with electrons, were ambiguous and required further analysis. As a consequence the “Radiation Protection for Advanced Equipment Design” project was launched. In that project the main focus was in the modelling of particle radiation attenuation with GEANT4 software and tuning the software parameters so that reliable correlation between simulation and actual radiation tests was achieved. As a result of this project the radiation attenuation of beam type radiation on the plate structure can be modelled with good accuracy.

From the composite material point of view, in the SIDER project a technology based on nanomaterials is proposed as an alternative for the radiation shielding. Requirements have been carefully studied and defined and detail analysis considering different scenarios performed before carrying out a validation campaign of both, the analysis and the shielding technologies developed. In previous projects with the foil option only wolfram foil has been studied. In this project a thorough evaluation is performed for alternative material options. The adhesion of the foil to the CFRP laminate has to be solved, too. In earlier projects no full scale structure has been exposed to radiation, only test samples (plates). When a full scale demonstrator structure is used information about radiation behaviour of joints and lead-ins (connector installations) is received.

There are issues that require further development as:
• The use of alternative High Density Materials (HDM)
• Optimum thickness portions of CFRP and the HDM,
• Manufacturability and handling of openings and joints.
• Development of analytical tools that simulate the radiation behaviour of composite structures
• Analysis of different/alternative radiation shielding techniques, lighter and/or easier to be integrated into complex geometry components
• Validation of the technology and the models in a real prototype.
These topics are included in this study and they are studied with experimental and simulation approaches.

Objectives

The main objective of this project is the development of the technologies and tools required to obtain lightweight, safe, robust and reliable composite structures.

Electronic housings are a massive part on the spacecraft. The new concepts for lightweight satellite show the possibilities of using advanced design based on composite housings. Nevertheless, the radiation effect in presence of composites is still scarcely investigated.

The project aims to review and develop radiation shielding of composite enclosures to high energy radiation in space. The radiation strategies, modelling and test for space equipment demonstrators will be performed. Countermeasures as tungsten layers and nano-conductive materials will be evaluated at simple samples to assess its shielding capabilities for the composites boxes. The activity will also adapt to enhance analytical tools and the capabilities, procedures and quality for the radiation facilities directed to composite testing, specially related to deep missions.

SIDER proposal is a continuation of previous ESA (AED, “Radiation Protection for Advanced Equipment Design”) and EC-FP6 projects (MULFUN, AST4-CT-2004-516089) projects, where members of the consortium have collaborated. The technological objectives are:
• Analytical tools and models for radiation design of the composite structures
• Assessment of different technologies for providing improved radiation shielding behaviour
  o Nanotechnology: Two different strategies will be followed: Doping of the bulk resin with nanofillers and infiltration of resin into buckypaper (thin preformed sheets of well-controlled and dispersed nanofiller networks)
  o Integration of foils
• Skilled handling and manufacturing of complex shapes components with brittle high thermal conductivity fibres.
• Study of manufacturability and handling of openings and joints
• Development of a test set-up and testing of a composite enclosure
• Validation of the developed technologies and analytical models by means of testing.

SIDER project strategy

The project has been divided into the following Phases:

WP1 is devoted to management and coordination activities of the SIDER project. In Phase 1 (WP2) mission scenarios have been analysed and requirements identified. The outputs of this Phase have been the basis of the following studies. In Phase 2 there has been a close collaboration between WP3, WP4, WP5 the corresponding composite structures have been implemented in the simulation package (WP3) and the development of different techniques to improve the radiation behaviour of composite structures has been carried out (WP4). Samples have been manufactured following different approaches (WP4) using a well-defined geometry and then, have been irradiated under various conditions (WP5). Experimental results have been compared to the simulated ones and the most promising approaches have been identified.

Samples have been designed such as to allow easy manufacturing and simple and accurate characterization of all relevant parameters such as size, specific mass, stopping power, thermal expansion coefficient, mechanical properties, etc.

In Phase 3 (WP6), after establishing acceptable agreement between simulation and experimental procedures in Phase 2, the structures have been optimized exclusively relying on simulations (WP6). This approach will significantly reduce time and cost of the hardware optimization procedure. Hardware has been designed, manufactured, tested and validated in a relevant environment.

An enclosure integrating the technologies developed in Phase 2 has been manufactured and validated. This prototype represents a step further to a more realistic scenario in the development of radiation shielding strategies of composite structures. This approach is very near of testing a real situation.

In Figure 1 the flow chart and the work breakdown structure corresponding to the SIDER project is presented.

Project Results:

WP2: Mission analysis and requirements definition

Centre Spatial de Liège (CSL) of the University of Liège (ULg) in Belgium has been involved in the simulation of radiation environment of typical space mission and in radiation testing.

The following aspects were studied in this WP:

o Definition of the orbits of study
o Calculation the irradiation levels corresponding to each orbit
o Identification of the test matrix

The purpose of simulation of the radiation environment was to identify radiation type (electrons, protons), calculate energy spectrum and flux in each orbit. From the commercial point of view Geostationary and Low Earth Orbits, which are used for telecommunication and remote sensing satellites, present the main interest.

The selected typical orbits and their maximum values of integral particle fluxes have the following parameters (Table 1). These parameters were used for the selection of the initial conditions and parameters (regarding the radiation) introduced into the SPENVIS software to get credible experimental data and minimize the amount of experimental investigations. Energetic spectrums of ionizing irradiation for these orbits were calculated. Composition of the space irradiation, which affect to the satellite during the mission at the selected orbits was calculated.

Test matrix and interconnections between tests and simulations were also identified. As a result of the collaboration of all the Partners involved in SIDER project, the strategy to be followed was clearly identified, indicating the inputs and outputs required from each WP, detailing the required test campaigns (type of irradiation tests, samples to be irradiated, etc).

The following test matrix was defined for SIDER project:

- The first test campaign was an initial investigation of behavior of several composite materials produced by partners in various irradiation conditions. The goal was to identify the more promising composites.
- The second test campaign purpose was to deeply investigate the radiation properties of the more promising composite structure (identified in the first test campaign), allowing Partners to validate and optimize their theoretical models.
- The last test campaign purpose was to irradiate a closed box of composite sample (prototype, simulating a real structure) and to compare it to aluminum box.

WP3: Analysis of the effects of radiation in composite structures
Simulations at material level
Sence has been responsible of the analysis and simulation of the selected shielding materials, and has had a major contribution in finding the optimal configuration for the selected materials. Due to the nature of the interactions and complexity of the enclosure compositions, analytical models are not sufficient for studies of radiation interactions in space environments. Therefore Monte Carlo simulations are required.

Geant4 simulation toolkit was selected as a basis of the modelling due to its functionalities. It has been designed and constructed to expose the physics models utilised, to handle complex geometries, and to enable its easy adaptation for optimal use in different sets of applications. The toolkit is the result of a worldwide collaboration of physicists and software engineers. It has been created exploiting software engineering and object-oriented technology and implemented in the C++ programming language. It has been used in applications in particle physics, nuclear physics, accelerator design, space-engineering and medical physics. Toolkit version 9.5 was used in the simulations.

The material descriptions were implemented in the simulations using the information that was given by Aalto and Tecnalia about the properties. In the first phase of the simulations, single layer properties were studied to give a better view about the performance of the individual layers. The simulations were divided in two parts, one studying the laminates and the other, layers with nanoparticles.

Following laminates were studied:
- Aluminium with thickness of 1 and 2 mm
- Tungsten of 50 and 100 µm
- Stainless Steel of 50 µm
- Prepreg of 215 µm

During the project it was found out that the solid tungsten was not ideal material for the manufacturing and was later replaced by 90 µm layer of tungsten alloy. This description was later added to the simulation model.

Tungsten nanoparticles were estimated to be spherical and positioned in symmetrically inside the nanolayers. To save CPU time, most of the simulations were made using 100 nm particle diameters. These were compared to samples with 50 and 70 nm particles. To save CPU time the carbon nanotubes were modelled as uniform material since their effect to overall attenuation is small. Sample of the lattice structure can be seen in Figure 2. In the sample the percentage of Tungsten nanoparticles is named to be 100%. However since the particles are spheres, they cover only about 51% of the volume. The rest of the volume is filled with carbon.

The effect of varying the portion of nanoparticles in samples was studied. In these simulations nanoparticle diameter of 100 nm was used to reduce the time needed to run the simulations. The overall layer thickness in the first stage was 100 µm. In the case of 100 nm particles, the distance and overall number was varied as follows:
- 100 % of W, pitch is 100 nm.
- 80 % of W, pitch is 125 nm
- 60 % of W, pitch is 166 nm

The space between the nanoparticles was filled with solid carbon with a same density as the nanotubes have.

Since realistic model would have random size nanoparticles, studies of the effects of varying the radius were made. Radii of 50, 70 and 100 nm were selected with sample composition of 80% of Tungsten and 20% of carbon nanotubes. The unit cell in 50 nm and 100 nm cases is similar; the only difference is the overall number of particles in the samples. Therefore the width of the sample was narrowed to 1 µm in order to study the scattering. The width of the scoring layer was kept at 1 cm so it would collect the radiation that is scattered off the main axis. The thickness of the sample was kept at 100 µm.

Effects of radiation were studied using a model of monoenergetic beams from point sources. Main part of the simulations focused on radiation that is perpendicular to the samples but effects of angular variations were also studied. Number of
particles per spill was varied from 104 to 106. Main parts of the simulations were done using lower particle densities. A higher particle density was used to verify the precision of the analysis.

The incoming particles and energy regions that were studied with laminates were:

- Protons of 1-100 MeV
- Electrons of 1-20 MeV
- Gamma radiation of 1-20 MeV

For nanostructures, due to the effects seen from the laminate structures, the input energy region was narrowed. It was seen that for the selected sample thickness it was sufficient to study:

- Protons, 5-45 MeV
- Electrons, 1-9 MeV
- Gamma radiation, 1-9 MeV

Dose and particle spectrum were measured by 300 µm thick scoring layer of Silicon. The layer was placed right behind the samples.

After the single layer properties were studied, full multi-layered sample descriptions were written. These included the sample descriptions of actual shielding composites that were used in the beam tests. The beam test results were used to validate the model descriptions before the optimization process. The simulation results were seen to match the measurements with high accuracy (Figure 2).

At the second test campaign, the simulation models were evolved to be accurate enough to validate the measurement results. Based on the simulations, measurements with faulty detectors or mix-ups with the samples were spotted and ranked out from the final data-analysis that was used in the optimization process.

The optimisation of the best combination of the composites and nanoparticles was made in comparison with a reference layer consisting of 2 mm of aluminium. The reference was used as upper boundary conditions for the thickness and mass for the composite. The optimization consisted of analysis of overall dose and attenuation behind the shielding for proton and electron irradiation.

As a result, a composite which provided mass savings and has similar or improved performance in comparison to aluminium reference was found. The optimal structure was adapted into the final shielding material that is used as a sole sample material in the third measurement campaign. The outcome of the optimization was the optimal number of layers, their composition and their position in the composite enclosure.

The performance of the optimized sample was studied using AP-8 and AE-8 models at LEO and GEO orbits. These distributions were used as an input to simulation model. It was found that the optimized sample improves the shielding at GEO orbit and responds comparably with the performance of aluminium at LEO orbit when comparing sample thicknesses of 2 mm.

Analytical tool development

Figure 3 represents the layout of the first version of the analytical tool, suitable for analysis of application of local shielding made of composite materials.

A 3-D model of the requested object is built in Autodesk AutoCAD environment as the integrity of geometrical primitives. The initial data in the form of depth-dose curves, and particle spectra are calculated previously outside of the analytical tool. With the use of sector analysis technique the program estimates shielding kind and thickness in the angular sectors around the point of interest. In the case of aluminium shielding the traditional approach is used for estimating of space radiation effects. When the program finds composite structure in the angular sector it calls the MULASSIS procedure performing 1-D Monte-Carlo transport of the space radiation through this structure to estimate the space radiation effect. The total radiation effect is estimated by summation on all angular sectors.

1 mm aluminium box with the four circuit boards in GEO environment, represented in Figure 4 was considered as an example. Assume that the points of interest IC1 and IC3 are in the centers of the circuit boards. Application of the traditional sector analysis technique indicates that ionizing doses for IC1 and IC3 are, correspondently, 2.405E+7 rad and 1.839E+7 rad. Assume that IC1 dose is out of our requirements and we need to reduce it up to IC3 level.

Figure 5 represents shielding and ionizing dose distributions around IC1 point in positive and negative directions of the coordinate system shown in Figure 4.

Figure 2

Figure 3

Figure 4

Figure 5
As it is evident from Figure 5, the main radiation exposure comes from the Y-direction and placement here the space radiation shielding made of composite material is decisive.

Figure 6 illustrates that placement of a small piece of composite shielding material at the defined location significantly reduces ionizing dose incoming from Y-direction. The calculations conducted with the help of the analytical tool indicate that application of the composite shielding material reduces overall dose on 32% up to the value of 1.647E+7 rad, which is sufficient in our formulation of the task.

Attempts to expand the above approach on solving of general task consisting in estimation of space radiation effects inside a composite box installed in a satellite was not successful because of huge time requested for simulation. Another approach, based on estimation of transforming of space radiation spectra after their penetration to the requested point inside a composite box installed into a satellite was proposed. Its layout is presented in the Figure 7.

To accelerate program execution precalculated datasets characterizing spectrum spreading of monoenergetic electron and proton beams after their passage through a shielding was used. The concept of application of these datasets is presented in the Figure 8.

WP4: Technologies to improve radiation behaviour of composite structures (from M to M18)

TECNALIA and AALTO have been working in the development of new laminate structures that are evaluated by analysis (WP3) and tests (WP5) in respect to their capability of attenuating the passing through particle radiation. TECNALIA has been concentrated in applying particles (CNT and wolfram particles) in the laminates and AALTO solution uses continuous foils (wolfram foil as high Z material and steel foil as medium Z material).

A common prepreg material has been used in all the laminates. The resin selected has to be suitable for aerospace environment, being the main demanded properties: low absorption moisture, low outgassing and high dimensional stability. In addition, to work with nanoreinforcement materials such as nanotubes, nanoparticles, the resin should have particular characteristics as low viscosity and high gel time. The MTM57 epoxy resin from CYTEC and the M40J fibre have been selected (MTM57, UD M40J 300g/m2 carbon fibre, 32%wt resin). The system can be cured at temperatures from 80 °C to 120 °C.

T4.1 Nanofiller engineered laminates – Nanofiller doped laminates

An in deep review of the information related to radiation shielding in composite materials was performed. Commercial carbon nanotubes (MWCNT), with a purity of > 90 % and wolfram nanoparticles were selected.

Some characterization tests were carried out to confirm the data given by the suppliers. The morphology of some tungsten nanoparticles was bigger than the dimension specified by the supplier (4.67μm, 906nm, 501nm). These results are not in good agreement with the data given by the supplier.

Two types of nanofillers with commercial availability have been considered: carbon nanotubes (CNTs) and tungsten nanoparticles. Moreover, the possibility of combining both approaches has also been considered.

Based on the selected materials (CNTs and tungsten nanofilbers), two approaches to integrate the nanomaterials in the composite structure have been studied:

- Bulk doping strategy. Integration of nanoreinforcements directly into the resin. Once the resin has been doped, laminates have been manufactured by hand lay-up and autoclave curing.

- Buckypaper strategy. One alternative to the doping strategy is the preforming of nanoreinforcements into thin mats with well-controlled dispersion and porous structure, so called in the literature “Buckypaper”. The buckypaper has been integrated into prepreg lay-up for later curing in autoclave.

Process parameters have been optimized and samples with different percentages of nanofilbers have been manufactured. The amount added to each sample has also been corroborated by simulation of the irradiation behaviour.

The work has been focused on the preparation, dispersion, homogeneization of nanofilbers into composite laminate for obtaining the required functionality. The target has been to optimize the two nanotechnologies proposed in order to obtain:

1. An optimal and stable dispersion of nanofilbers into the final laminate
2. A suitable nanofiller/resin interfacial bonding
3. Preservation of the integrity of nanoreinforcements during integration process.
For each strategy, TECNALIA has performed several trials.
• Doped resin: Trials incorporating W nanopowders and CNT in different samples have been performed. Both nanomaterials have also been combined and incorporated in the resin. The resin used is the ARALDITE LY 1556, compatible with the MTM57 epoxy resin of the prepreg.
• Buckypapers:
  o CNTs and nW incorporated in the buckypaper:
  o CNTs coated with W and incorporated to the buckypaper
From the tests and manufacturing trials performed it was concluded that the epoxy resin can be doped with high percentage of W particles (around 80 %) keeping manufacturability parameters (viscosity around 4000-5000cp). A maximum content of 0,5% CNT and 30% W can be achieved when combining both fillers to dope the epoxy resin
Related to the buckypaper strategy, higher CNT loading than with the doped resin can be obtained. In the same manner, high contents of CNT in combination of W nanoparticles can be obtained (50 % CNT+50 % W). Thanks to the CNT network W nanoparticles decantation is not produced
Both, doped resin and buckypapers could be integrated in the standard prepreg processing in autoclave and complex shape parts could be manufactured.
Results obtained following the buckypaper strategy show that the mechanical properties analyzed (interlaminar shear strength) decrease approximately 50%. This drop is attributed to the delamination observed by cross sectional analyses.
In order to evaluate the influence of the nanofillers in the properties of the laminates, doped laminate coupons have been submitted to a characterization test campaign, being the tests performed the ones indicated in Table 2:
Results obtained indicate that introducing a central layer of nanotungsten doped resin in the prepreg material, does not modify significantly the properties of the laminates. Related to buckypaper strategy there is a detriment of ILSS, approx. 50% (delamination, it is necessary to improve the adhesion between prepreg and buckypaper).
Light microscope analysis shows that the integration of doped resin into the laminate is very good (Figure 9), however, a delamination can be observed in the sample containing a buckypaper (Figure 10).

Throughout the project, samples have been prepared and submitted to the different radiation test campaigns (first test campaign, second test campaign, prototype testing)
In the first test campaign, laminates including both doped resin layers and buckypapers in the laminate were manufactured following the indications and results obtained in the simulations performed under WP3. NUMBER OF SAMPLES... For the first radiation test campaign TECNALIA manufactured 22 samples were prepared for proton irradiation 8 samples with doped resin and 14 with buckypapers (2 samples per material). The sample size was 20 x 20 mm. For electron irradiation one sample was manufactured (50 mm x 50 mm in size).
As a result of the first test campaign, the materials to be further developed were selected: doped resin with 80 % W aprox and buckypaper (6%CNTand 94%W). The work was then focused in the optimization of nanofiller doped laminates based on both strategies: direct resin bulk doping and buckypaper.
Samples for the 2nd Test campaign were manufactured. In Table 3, details related to the samples (100 mm x 100 mm) provided to carry out this test campaign are depicted.

T4.2 Integration of foils
The work of Aalto in the SIDER project can be categorized as follows:
1. Foil selection and composite materials selection together with Tecnalia
2. Manufacturing of test laminates with foil
3. Characterization of laminates with foils
4. Minimizing cure induced shape distortions of asymmetric laminates
5. Design of enclosure and its molds
The primary foil material was studied. The requirement for the material was that it should have high atomic number i.e. it should be a dense material. The materials listed in Table 4 were studied in detail. Tungsten was considered as an optimum material for SIDER purposes as it has good mechanical and physical properties and it is effective in radiation shielding, too.
For the first radiation test campaign Aalto manufactured for proton irradiation 19 samples with foil and one aluminum reference. The sample size was 20 x 20 mm. For electron irradiation one sample with foil was manufactured. Its size was 50 x 50 mm. For the second test campaign Aalto manufactured two samples with foils by size 100 x 100 mm. Also one aluminum reference was delivered.

Characterization of laminates with foils included following investigations:

- Mechanical characterization: tensile strength and modulus.
- Foil adhesion characterization
- Electrical characterization: electrical resistivity in x, y and z directions.
- Microstructural characterization (SEM).

Mechanical characterization revealed that pure tungsten is brittle and due to manufacturing method (cold rolling) also structurally layered, which made it weak. Therefore pure tungsten is not viable for structural applications. However, tungsten heavy alloy (WHA) has almost identical radiation attenuation properties as the pure tungsten, but it is ductile and is suitable for structural applications. WHA was selected to be used in the box like housing, which was tested in the third test campaign.

For structural integrity of the hybrid laminate one of the most critical items is the surface treatment of the tungsten foil. Several optional treatments were tested. These included mechanical treatments, chemical treatments and additional coatings. Tested coatings included a diamond like coating with two thicknesses and copper based coating. Mechanical tests for adhesion characterization included lap shear, cracked lap shear and pull-off tests. The primary chemical treatment was hydrofluoric-nitric-sulfuric acid treatment with different dwell times. It turned out that the dwell time has a significant effect on adhesion. Short times like 1 or 3 minute gave better results than the 5 minute dwell. In lap shear tests 1 and 3 minute hydrofluoric-nitric-sulfuric acid treatment gave almost as good results as the 1 μm DLC coating. In pull-off tests the best results were recorded for 0.1 μm DLC coating, for grit-blasted sol-gel treatment and for copper coating.

Finally a 0.1 μm DLC coating for the tungsten foil was selected to be used on the foils for the test enclosure. This method provides very good adhesion and it also provides long working time after the treatment. The drawback of the method is that it is done with a vacuum deposition process, which requires special equipment.

Electrical resistivity was measured with Van der Pauw’s method at Aalto from samples of size 72 x 72 mm. Total of four samples were tested. Two samples included a steel foil and two were pure CFRP laminates. There were two pairs of otherwise samples but the one included a steel foil and the other did not. The measurements at Aalto were not very reliable due to built-up test arrangement. Therefore the same samples were cut to size 45 x 45 mm and sent to Tecnalia for second measurements. The behavior of samples was according to assumptions. Results show that the addition of a central layer (doped resin or tungsten foil), generally speaking, do not influence in the through thickness electrical conductivity.

Microstructural characterization was done with optical microscope and SEM. Main interest was the foil CFRP interaction. One of the most interesting findings was the nature of the high purity 50 μm tungsten foil. As it can be seen in Figure 11 the foil has layered structure, which made it very weak interlayer loads.

WP5: Radiation test method evolution / definition

The three irradiation test campaigns are summarized in Table 5. The setup used for protons in the first test campaign is described in Figure 12 and the results obtained for protons in Figure 13.

In the Y-axis stopping power of materials for 20 MeV protons is shown. The samples above the line are relatively better than the aluminium sample and the samples below the line better in absolute attenuation. The samples above the line are generally thicker than the reference since more interaction length to attenuate energy than with the reference and the ones below the line is needed.

From the plot it can be seen that composites that are lighter than aluminium and also composites that are thinner than the 2 mm reference and at the same time keeping the shielding performance of the reference can be manufactured.

The plot is useful to see the effects in changing the order of the laminates and the thickness of the doped resins. This information was used in the optimization process.

For the 2nd test campaign, protons testing done were 3D mapping of energy spectrum measurement behind four type of
sample (AALTO A3, TEC17, TEC18 and Al for reference). Measurement setup has been adapted to allow measurement of tilted samples. For each composite sample, spectrums have been recorded at 12 different positions (6 at normal incidence and 6 for sample tilted at 60°). Aluminium measurement was made for reference each time the experimental parameters were modified. 58 spectrums were obtained (36 for composite samples, 3 on composite for calibration, 19 on Al for references). Electron testing were done with 6 MeV beam in air with a dose of 1 Gy (water), doses were measured after samples with optically simulated luminescence (OSL) dosimeter. Results are given hereafter:

Neutrons testing results do not show any improvement for tested composite samples.

WP6: Composite enclosure validation
T6.1: Radiation Analytical Model
For the final measurements, a full simulation model, consisting of model of the test enclosure that was built for the third measurement campaign, was made. With the model the expected results of the proton and electron irradiations in the third measurement campaign were estimated.

The main outcome of the work has been a composite structure that consists of both tungsten laminates and layers with nanoparticles giving unprecedented properties to the shielding. At the same time the mass of the shielding is smaller than when it is made from aluminium.

On the other hand, the analytical tool was applied to estimate LEO and GEO space radiation effects inside a satellite in the presence of radiation shielding material. Figure 16 illustrates 3-D model of a satellite built for this task.

In LEO and GEO environments space radiation effects were estimated for:
• absence of the satellite equipment case;
• aluminium case with wall thickness of 0.518 g/cm², traditional sector analysis technique based on depth-dose curves usage;
• aluminium case with wall thickness of 0.518 g/cm², analytical tool approach,
• case made of radiation shielding material with wall thickness of 0.518 g/cm², analytical tool approach.

The results of conducted simulations are represented in Table 6 and Table 7.

The represented data allows making conclusion that the results, achieved with the use of the analytical tool and traditional sector analysis technique in the most cases demonstrates satisfactory agreement.

In whole, it can be stated, that the main goal formulated for the analytical tool, consisting in rapid and obvious application of space radiation shielding materials in satellite engineering practice is achieved. Developed analytical tool makes it possible conducting multiple simulation runs to define optimal location, shape, and thickness of space radiation shielding materials to protect certain satellite component or to estimate the space radiation effects inside a box made of composite material and placed inside a satellite. Up to date the similar tasks have been solved with the usage of Monte-Carlo technique and required several hours for simulation. In this case the simulation is completed for several minutes, depending on complexity of a satellite 3-D model.

Quality of the datasets, describing particle passage through space radiation shielding materials is critically important for accuracy of the analytical tool results. Development of these datasets with the usage of GEANT4 tool is extremely time-consuming. Thereby building of the datasets on the base of experimental data looks attractive. A test campaign as a part of activities to support development of the analytical tool was conducted at the electron accelerator Microtron M30 in Uzhgorod Institute of Electronic Physics of Ukrainian Academy of Science. The test matrix is presented in Figure 17.

Analysis of the obtained results indicates insufficient accuracy of the applied technique because of electron scattering and production of secondaries. The technique of experimental estimation of particle spectra behind a shielding for analytical tool needs improvements.

T6.2 Design and manufacturing of enclosure
Optimal laminates for radiation attenuation purposes are often asymmetric. This makes them distort after curing. Those
distortions can be minimized by orienting CFRP layers in definite way. This phenomenon was studied first by free standing laminates. Koerselman used an analytical model to predict shape distortions. The operation of the model was studied with a (902/02) laminate of size 200 x 200 mm with temperature difference of 100 °C. In Figure 18 is shown the actual laminate and in Figure 19 the modeled laminate. As can be seen and as it was verified by displacement measurements, the correlation was good. Breuer-Harberts further developed the model to include boundary condition, where one side of the plate is clamped. He modeled and manufactured an asymmetric laminate, which included a metal foil and also an adhesive layer inside CFRP layers. The measured and predicted displacement fields are shown in Figure 20. As it can be seen the correlation was good also in this case. The method was used to define the layer orientations of the laminate used in the test enclosure.

The purpose of the third test campaign was to study the radiation behavior of a realistic but simplified enclosure. Special attention was paid to testing of corner joints and also a possibility to make cut-outs for connectors was reserved. The laminate structure was optimized for radiation attenuation according to the defined space environment and based on the experience gained during the project. Mechanical, thermal and electrical aspects were mainly ignored in the design. The enclosure and its molds were designed by AALTO and TECNALIA manufactured the enclosure. The elements i.e. walls and caps are mechanically attached to each other. The parts geometry was kept simple because an asymmetric laminate structure provided already adequate challenges for manufacture and assembly.

One major challenge for the box design was the fact that the box consists of an asymmetric laminate due to optimum radiation attenuation reasons. This is that the panel will distort significantly during curing if no special actions are taken. Following the lay-up orientations defined by AALTO, TECNALIA performed trials to assess the correct manufacturing of the prototype (electronic housing). Finally, the prototype was manufactured with the optimized lay-up sequence obtained based on the results of the irradiation tests and the simulations.. In Figure 21, the CFRP and the aluminium housings developed are depicted.

T6.3: Radiation Test Campaign and Validation
The CFRP housing and its aluminium counterpart have been submitted to the following test campaign:
- Proton testing (2 rotations): with the beam in the centre of the wall and in the joint (to test the possible leakage effects).
- Electron testing: pile up the walls of the housing in order to evaluate the thickness influence.

For the proton testing, two radiation doses measuring devices (RADFET and OSL) were installed inside the box, as shown in Figure 22.

WP7: Exploitation and dissemination
T7.1. Technology Assessment
Deliverable D7.1 “Technology assessment“ discusses the potential and challenges of the developed concept. However, one should notice that the main objective of this study was to develop methodology and procedures to design lightweight composite enclosures for spacecraft electronics. Although it is premature to evaluate in detail the cost and mass effectiveness of the developed laminate structure, some preliminary calculations have been performed.

This study has been concentrated in the radiation attenuation of the laminate structure of a generic enclosure. This behaviour is now better understood than before the study. However, as other important factors like mechanical stiffness and strength, thermal conductivity and electrical performance could not be included in the study.

T7.2. Technology Implementation Plan
A Technology Implementation Plan has been prepared which explores the opportunities for exploitation of the results of the SIDER project; this includes use of the research for both the academic and the industrial context, the intended exploitation by the project partners and the opportunity to employ and build upon the technologies that have been developed in the context of SIDER project.
T7.3. Dissemination Plan

An update of the dissemination plan has been submitted (D7.3) Activities carried out and foreseen in SIDER are summarized in Table 8 and Table 9.

Potential Impact:
The current trend in space is to reduce weight, so lightweight composite materials are increasingly used. Around 9% of the total composite shipments in Europe (1,540,000 tonnes and 5.2 BEuro) are used in aerospace / defence.

Radiation shielding is becoming a crucial parameter for electronic components in space because modern electronic components are produced with nm scale process technology and hence are more sensitive to radiation (i.e. FPGA can be badly affected with total dose less than 100 kRad).

Thanks to composite structure, shielding shape can be adapted to fit critical parts of the satellite (i.e. electronic) and composite composition and thickness can be adapted within a given shielding to be more efficient for some components (some electronic components are more sensitive to radiation and a given shielding could be thicker in front of that particular component).

The main objective of SIDER project is to develop and test a new type of radiation shielding material for space applications. These new shielding solutions are lighter than the conventional ones (typically 2-mm thick aluminium) and therefore will help reducing the cost of a satellite (by reducing their weight) or will allow, for the same weight, to carry more payload for the same price.

From the results obtained, it can be concluded that the SIDER project allows reducing, without compromising safety, the weight of the structural elements at GEO orbits. The material developed is more efficient than the aluminium. For LEO orbits, promising results were obtained by simulations. However, it has not been possible to validate the results.

The simulation models that were developed allow wider studies of multi-layered structures and nanofillings using various materials beyond the scope of this project. Since part of the modelling consisted of importing CAD models directly to the simulation geometry descriptions, the developed methods allow import of models of any type and of any complexity. This can be used in the shielding studies and development of various applications where mass savings is critical.

The analytical tool intending for estimation of space radiation effects inside a satellite in the presence of advanced shielding materials is also a result of SIDER project. The analytical tool allows satellite designers conducting of rapid and multiple simulations to achieve optimal position, configuration, and thickness of space radiation shielding inside a satellite with minimal mass and volume expenses. Up to date the similar tasks have been solved with the use of Monte-Carlo technique and required several hours for simulation. In our case the simulation is completed for several minutes, depending on complexity of a satellite 3-D model. The developed tool is in agreement with ESSS standards and its application can be easy integrated into traditional practice of radiation designing of a satellite.

From the nanotechnologies point of view, manufacturing approaches to incorporate the nanofillers into the laminates have been developed. Three different strategies have been followed: doping of the resin, incorporation of CNT and nanoW in buckypapers and synthesis of C-W on the CNT of Buckypaper. From the results obtained, the doping of the resin has been considered as the most promising approach. Process parameters have been optimized and samples with different percentages of nanofillers have been manufactured.

The doped resin has been introduced as an additional layer in the laminate. Further studies in the subject would allow the manufacturing of a prepreg with the already developed doped resin.

Related to the integration of high Z foils in the laminate, the main results are:

- WHA should be used instead of high purity tungsten as foil material
- DLC coating on tungsten foil provides high strength adhesion to CFRP
- A code for minimising cure induced shape distortions of asymmetric laminates was developed

Tungsten is an optimum High-Z foil material in composite laminates with good radiation (electrons) attenuation. However the brittle nature of high purity tungsten makes it problematic in structural applications. WHA has almost identical radiation
attenuation properties than high purity tungsten. Its mechanical properties are also alike but it is ductile and not brittle. This makes it preferred High-Z material in structural applications.

Several surface treatments for tungsten foils were reviewed and tested. The purpose was to find a method that provides high strength adhesion and would be easy to perform. DLC coating provides excellent adhesion and it is stable after its implementation. Special equipment is required to make the DLC coating.

As hybrid laminates, which include layers of different materials, are optimised for radiation attenuation, the outcome is typically an asymmetric laminate structure. That kind of laminate experiences shape distortions after elevated temperature cure. To minimise those shape distortions CFRP layers can be orientated in optimum angles. Naturally structural requirements of the laminate have to be taken into account, too. Aalto developed a code, which calculates the layer angles for minimum shape distortion.

The technologies developed here can be applied for other than just protecting spacecraft electronics. Manned long endurance space flight could benefit about the work done in SIDER project.

The manufacturing of the final prototype has been a challenge because, a combination of both material strategies was considered as the optimized solution from the manufacturing point of view.

The tests campaigns carried out allow validating the results serve to cross-check the results obtained in the simulations and to validate, for a given mission, the radiation shielding behaviour of the structure developed.

D7.3 lists all scientific (peer reviewed) publications relating to the foreground of the project) and all dissemination activities (publications, conferences, workshops, web sites/applications) carried out within SIDER project.

Two Master’s Thesis have been prepared in the project at Aalto. The first one was done by a student from the Delft Technical University and the second one by international Master’s student at Aalto. The first one was done in the beginning of the project and it concentrated on the optimisation of laminates with metallic foils. It also included studies in surface treatment of tungsten foil and shape optimisation of a free standing hybrid laminate. The second thesis was prepared at the second half of the project and it concentrated in the shape optimisation of partly clamped asymmetric laminates. It also included the design of the box like enclosure, which is used in the third radiation test campaign.

The surface treatment on tungsten foils has turned challenging. There are not many previous studies on the subject. However, as the durable surface treatment is essential for the use of the developed hybrid laminate in radiation attenuation function, Aalto has researched the topic in depth. The research, especially the final tests are running till the end of SIDER project. Thus the results will be reviewed in the updated Deliverable D4.5 and in two scientific journal articles. These articles will be prepared and published after the SIDER project.

List of Websites:

http://www.sider-project.eu/

Related information

| Result In Brief | Space radiation protection |

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