ESA Study Contract Report

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ESA Contract No: 400011215	SUBJECT: NANOCOMP - Nano-enabled Fibre Reinforced Plastics for Space Applications	CONTRACTOR: HTS GmbH
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ABSTRACT:

FINAL REPORT

The main objective of spacecraft structural components is to protect other components and to provide a sufficient mechanical stiffness to keep equipment and parts together. Beside low mass and mechanical requirements also thermal and electrical properties of the used materials are critical for space application. Usually lightweight metal alloys have been used to suit all requirements. Recent development has shown that lightweight fibre-reinforced plastics can replace metal components in many cases and help to reduce the mass considerably but has lower thermal and electrical properties. However these disadvantages can be reduced by the implementation of carbon nano species within the matrix.

The first objective of this project was therefore to characterize by test, the mechanical-, electrical-, thermal-, and electromagnetical shielding properties of representative samples of nano-enabled carbon fibre reinforced plastics to investigate their implementation in future space applications.

The second objective was to proof the sample test results by test of representative spacecraft structural component made from the same material. For this dedicated test procedures were developed and a comprehensive test campaign was performed.

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HTS

Executive Summary Report

Nano-enabled Fibre Reinforced Plastics for Space Applications

ESA Contract No. 4000112157/14/NL/PA

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1 GENERAL

1.1 Scope

This document summarizes the tasks performed and the results achieved during the ESA GSTP study NanoCOMP under ESA Contract No. 4000112157/14/NL/PA “NANOCOMP - Nano-enabled Fibre Reinforced Plastics for Space Applications” which has been carried out by HTS GmbH in cooperation with Adamant Composites Ltd. (ADA), being separately contracted, during January 2015 to August 2017.

The report covers the following aspects:

- Background and objectives of this activity
- Work programme
- Market Potential Analysis within a State of the Art Review
- Definition of the Requirements and Reference Mission Parameters
- Description of the Concept to the Final Design
- Analytical Assessment
- Procurement, Manufacturing and Assembly
- Tests description and Results
- Conclusion and outlook

1.2 Change record

Issue / Revision	Date	Responsible	Description of change
1 / 0	21.08.2017	M. Oswald	Initial Issue

1.3 Applicable Documents

AD 1	ESA Contract No. 4000112157/14/NL/PA “Nano-enabled Fibre Reinforced Plastics for Space Applications”
AD 2	Appendix 1 to ESA Contract No. 4000112157/NL/PA “Nano-enabled Fibre Reinforced Plastics for Space Applications” – Statement of Work

1.4 Abbreviations

AD	Applicable Document
ADA	Adamant Composites Ltd.
CFRP	Carbon-Fibre-Reinforced Plastic
CNF	Carbon-Nano-Fibre
CNT	Carbon-Nano Tube
EMC	Electro-magnetic compatibility
EMI	Electro-magnetic Interface
ESA	European Space Agency
EDS	Electro-static discharge
ES	Electro-magnetic shielding
HTS	Hoch Technologiesysteme Coswig GmbH
Ne-CFRP	Nano-enabled Carbon-Fibre-Reinforced Plastic
PCB	Printed Circuit Board
RFI	Radio-frequency Interface
RD	Reference Document
UD	Unidirectional

2 BACKGROUND AND OBJECTIVES OF THE ACTIVITY

The main objective of spacecraft structural components is to protect other components and to provide a sufficient mechanical stiffness to keep equipment and parts together. Beside low mass and mechanical requirements also thermal and electrical properties of the used materials are critical for space application. Usually lightweight metal alloys have been used to suit all requirements. Recent development has shown that lightweight fibre-reinforced plastics can replace metal components in many cases and help to reduce the mass considerably but has lower thermal and electrical properties. However these disadvantages can be reduced by the implementation of carbon nano species within the matrix.

Nano-scaled filler materials for thermosetting plastics such as carbon nanotubes (CNT) or carbon nanofibres (CNF) have gained remarkable interest for the improvement of thermal and electrical conductivity as well as of fracture toughness of composites. In contrast to conventional fillers such as carbon black or metal powders CNT and CNF can achieve significant improvements at comparatively low filler contents. This enables preserving the mechanical advantages of carbon fibre reinforced plastics (CFRP) in terms of strength and stiffness as well as the processability of the matrix. Especially compared to metal powders the carbon fillers benefit from their low density and non-corrosive properties. This makes CNTs and CNFs ideal candidates for incorporation into conventional CFRP structural and functional parts.

The first objective of this project was therefore to characterize by test, the mechanical-, electrical-, thermal-, and electromagnetical shielding properties of representative samples of nano-enabled carbon fibre reinforced plastics to investigate their implementation in future space applications.

The second objective was to proof the sample test results by test of representative spacecraft structural component made from the same material. For this dedicated test procedures were developed and a comprehensive test campaign was performed.

3 WORK PROGRAMME

In order to achieve these objectives, the project work was broken down into the following five steps, which are described in detail hereafter:

- Identification of potential applications of nano-enabled CFRP materials in space equipment and selection of one pilot application
- Designing a representative demonstrator of the selected application
- Manufacturing of representative material samples for test on material level
- Manufacturing of a conventional- and a nano-enabled demonstrator
- Testing on sample- and demonstrator level to compare the performance of the nano-enabled CFRP to a conventional solution and assessment of results

The study logic can be seen in Figure 3-1.

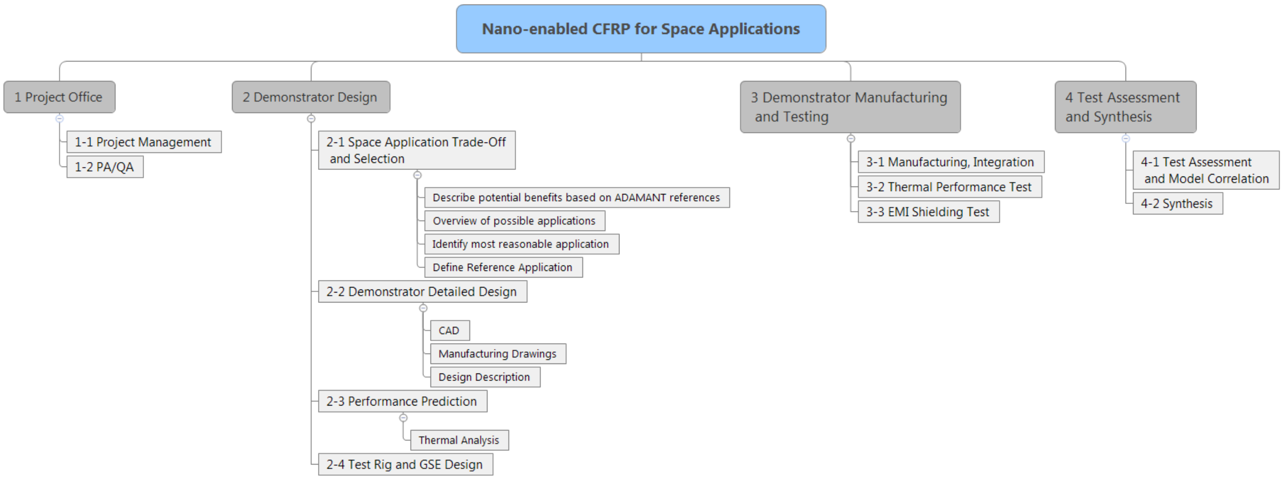

Figure 3-1: Work logic of the project.

4 ACHIEVEMENTS

4.1 Potential space applications of nano-enabled CFRP

In close discussion with ADAMANT Composites Ltd. the following applications for space missions and space technology were identified, which may potentially benefit substantially from nano-enabled CFRP materials and its benefits:

- Protection against Electro-magnetic Interference (EMI) and Radio Frequency Interference (RFI) as well as Electro-static Discharge (ESD) protection using lightweight, non-metallic components
- Utilisation of thermal properties of nano-enabled CFRPs
- Utilisation of improved mechanical properties in terms of stiffness, damping and damage-behaviour of nano-enabled CFRPs

The following potential equipments, which have already been developed or used by HTS, have been identified to potentially benefit substantially from nano-enabling:

- Lightweight electronics box
- Honeycomb panel
- Collapsible flexible hinge

Following a detailed trade-off the lightweight electronics box has been selected as the most promising demonstrator application.

4.2 Design of the pilot application demonstrator

4.2.1 Mechanical and electrical design

The overall demonstrator consists of a closed box made of CFRP with cut-outs for several Sub-D connectors and houses printed circuit boards (PCB). The box is an assembly of two side frames, one middle frame, one bottom frame, two mounting flanges and the top cover. The internal parts of the demonstrator can be seen in Figure 4-1 with the main structure parts.

The main dimensions of the demonstrator are 350 mm (length) x 120 mm (width) x 85 mm (height). The overall assembly structure is shown in Figure 4-2 which provides additional information about the integration sequence.

The PCBs are only dummy panels. The only purpose of these boards is to simulate a certain thermal load using resistive heating. The PCBs of PCB-type 1 are the two PowerPCBs with an electrical resistance of 160 Ω each. The PCBs of the PCB-type 2 are four DataPCBs with an electrical resistance of 95 Ω each.

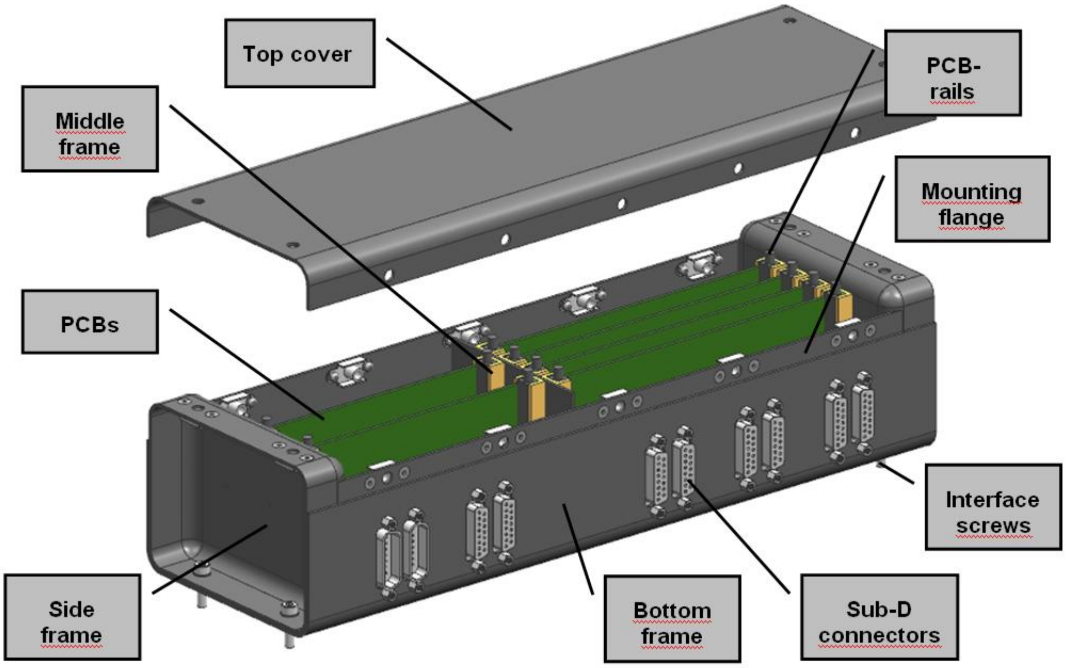

Figure 4-1: CAD model of the demonstrator (top cover off)

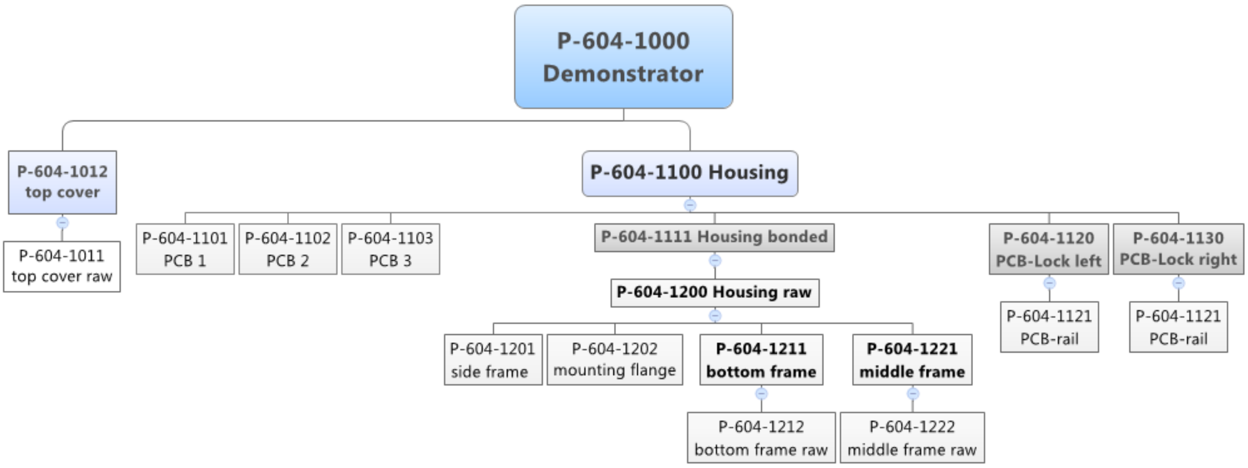

Figure 4-2: Demonstrator assembly structure

4.2.2 Material Specification

There are 6 different materials used inside the electronic box. The housing is made exclusively from CFRP with its following material specification:

- UD-prepregs with 300mm width and areal weight of 184g/m^2
- Fibres: T700S (6K) from Torayca (FAW = 125g/m^2)
- Resin: Cyanate ester matrix system

HTM110 from Cytec

- Fibre volume content = 60% / Resin weight = 32%
- Lamination sequence: (0,30,-30,90,45,-45)symmetric
- Material properties according to the datasheets:

The aluminium PCB-rails are made of:

- EN-AW 6082

The material for PCB dummies will be:

- FR4 (thickness 1.6 mm)

The adhesive bonding between the CFRP parts and also the PCB-rails will be realised with a highly conductive off the shelf adhesive qualified for space

- 3M™ Thermally Conductive Epoxy Adhesive TC-2810

The standard parts like screws and washers will be made of:

- Stainless steel (1.4301)

The floating anchor nuts will be made of:

- 25CrMo4 steel with passivation

The design of the nano-enabled demonstrator is completely the same as the conventional demonstrator. The only significant difference is the nano-enabled CFRP Prepreg material which gives the best possibility to measure the influence of nano-enabling.

This nano-enabling of all the prepreg-layer will be done by ADAMANT Composites. They have established a process to implement carbon-nano-species at prepreg-level. With this nano-enabling it is possible to influence the material properties towards the desired values. After enabling the material with nano-particles it can be handled and proceed like the normal prepregs.

4.2.3 Thermal Simulation

Prior to the thermal testing a rough estimation regarding the maximum temperatures within the demonstrator box was necessary. Therefore a thermal analysis has been conducted to gain values as test prediction.

The results of the first analysis can be seen in Figure 4-3. The resulting temperatures are quite high, which means that the thermal load must be reduced for ground-based testing to prevent damage and failure of the PCBs. In the current configuration a maximum thermal load of 11 W is possible. This can be seen in Figure 4-3 as well.

The figures show that the thermal conduction along the PCBs is not good and limits the effect this heating has on the temperature of outer box. A possible way forward would be the use of aluminium-core PCBs. The result of a simulation, using 1.5mm aluminium with an outer copper (35µm) and epoxy (100µm) layer can be seen in Figure 4-4. Using metal-core PCB thermal power of up to 38 W could be used, which will result in higher measureable temperature differences at the demonstrator box.

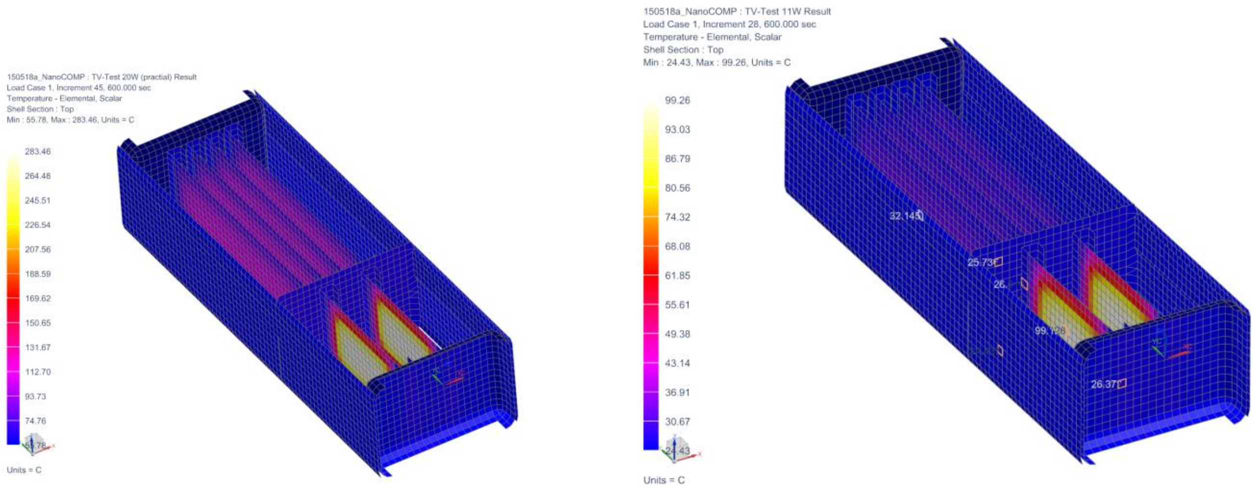

Figure 4-3: Temperature of the box applying 75 W vs. 11 W total thermal load.

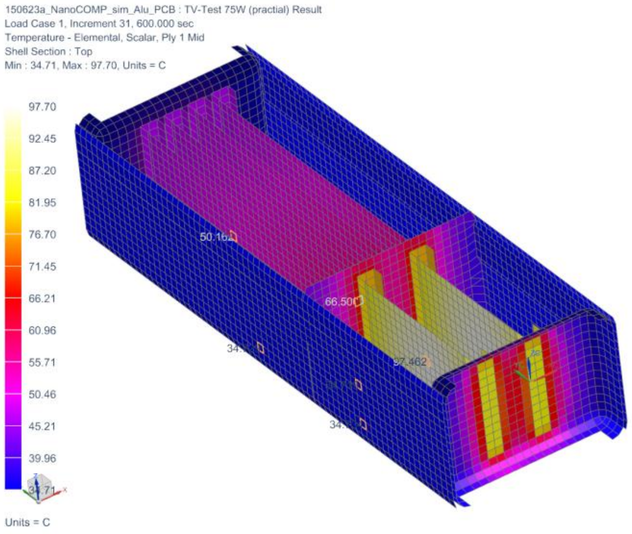

Figure 4-4: Temperature of the box using metal-core PBCs and applying 38 W total thermal load.

4.3 Manufacturing and Assembly

For the planned mechanical, electrical and thermal tests, several samples and demonstrators parts were built. To compare nano-enabled CFRP and conventional CFRP, the demonstrator parts and the test samples were produced with both materials.

Besides the nano-enabling, also the manufacturing of the CFRP-parts and CFRP samples using prepregs and an autoclave process was conducted by ADA. The cutting and mechanical post processing was done by ADA, ATECH GmbH and HTS.

4.3.1 Sample Phase

For the basic testing the following samples were produced:

- mechanical tests including tensile and shear tests: 12 samples
- electrical tests including volume- and surface conductivity: 12 samples
- thermal testing including steady-state thermal conductivity: 3 samples
- electromagnetic shielding performance: 4 samples were produced

4.3.2 Demonstrator Phase

During the initial production of the demonstrator parts, manufacturing flaws occurred which lead to wrinkles, dry laminate and poor surface quality. The parts could not be properly used for the test, therefore a 2nd batch of nano-enabled demonstrator parts were produced, which have been of better quality and used for the demonstrator test.

The overall assembly process includes the bonding of several parts using thermal conductive adhesive and the integration of Sub-D connectors and PCBs into the electronic box. The integration of the electronic boxes has been implemented by HTS.

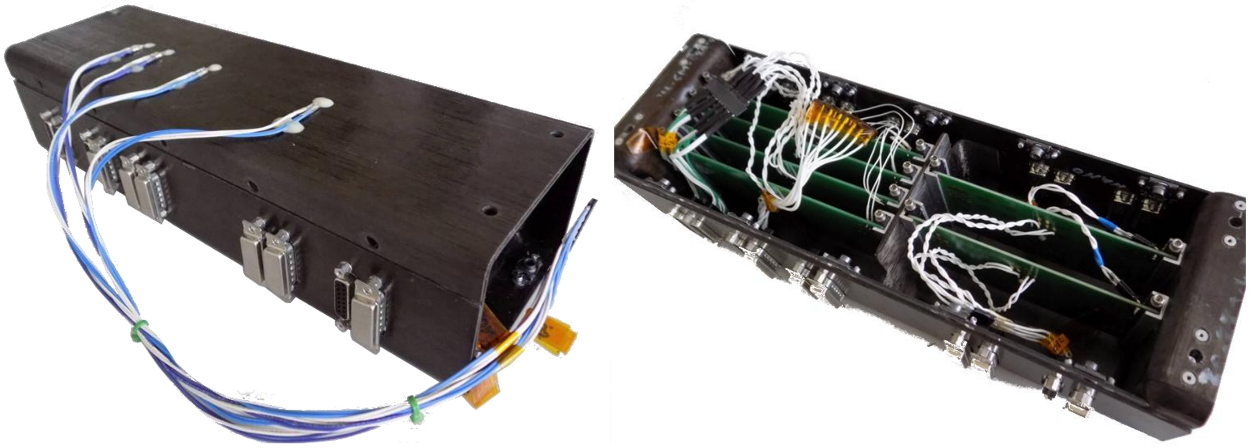

Figure 4-5: Assembled ne-Box with temperature sensors on the top-cover; opened box.

4.4 Testing

To verify the NanoComp-material performance, multiple tests were performed in two stages:

- Material sample tests, to characterize the basic material properties
- Demonstrator tests, to characterize the performance gain at demonstrator level.

4.4.1 Sample Tests

In order to characterize the change due to the nano-enabling process mechanical, electrical and thermal tests have been implemented. Therefore tensile- and shear tests, surface- and volume resistivity tests, thermal conductivity tests and electromagnetic attenuation tests have been done.

A summary of exemplary sample test results can be found in Table 4-1.

Based on the test results significant change of material properties has been identified. Most of the results are very promising but not all properties have changed in a positive manner.

Table 4-1: Summary of selected test results. Improvement of nano-enabled CFRP compared to conventional CFRP. Trends depend strongly on test setup and CFRP sample layup.

	Property	Trend
Mechanical	Stiffness	- 14.5 % to **+9.1** %
	Max. Stress	-42.5 % to **+13.4 %**
Electrical	Surface resistivity	**-57.4 %**
	Volume resistivity	+1260 %
Thermal	Thermal conductivity	**+257 % to +287 %**
Electro-Magnetical	Attenuation	**-26 dB** to +7 dB

4.4.2 Demonstrator Tests

The tests of two demonstrator electronic boxes have been implemented to assess the impact of the nano-enabling process in a real application. Therefore tests were implemented with a box made of reference material and with a box made of nano-enabled CFRP. These tests include thermal performance in ambient and vacuum environment and electromagnetical attenuation.

The scope of the thermal test is to check if the addition of nano particles leads to a better thermal performance of the electronic boxes. Due to the high thermal power of the electronics in such a box, a fast dissipation- and therefore high conduction of the thermal power is desirable. In spite of every effort it was not possible to get nano-enabled CFRP layup which has the same thickness as the reference material. This may have caused slightly differences within the following results.

The scope of the electromagnetic shielding (ES) tests was to investigate if the proposed lightweight CFRP box may be suitable for applications where sensible electronics have to be protected from strong electromagnetic fields, e.g. near to radar antennas. Within the tests it shall be assessed if the nano-enabled electronic box shows a better shielding performance compared to the reference box.

The electromagnetic attenuation results show no clear tendency whether the nano-enabled or the reference material has a better attenuation. At certain frequencies the attenuation drops down to zero, which may be caused by resonance and gaps within the assembly of the box. In general the attenuation is significantly lower compared with the basic material tests, which means that a higher damping is possible if the demonstrator is manufactured with a less amount of gaps and cut-outs.

Similar to the material sample tests, the nano-enabled material shows a better thermal performance. Due to a higher thermal conductance, the observed thermal hot-spots are colder compared with the reference box. Additionally it can be found, that the temperature distribution is slightly better with the nano-enabled material yet it is not uniform. This behaviour can be found in all test series. An example is shown in Figure 4-6.

The internal temperature on top of the PBCs has been monitored to prevent overheating of the PCBs. In Figure 4-6 it can be seen that the temperature difference between reference- and nano enabled box is very small.

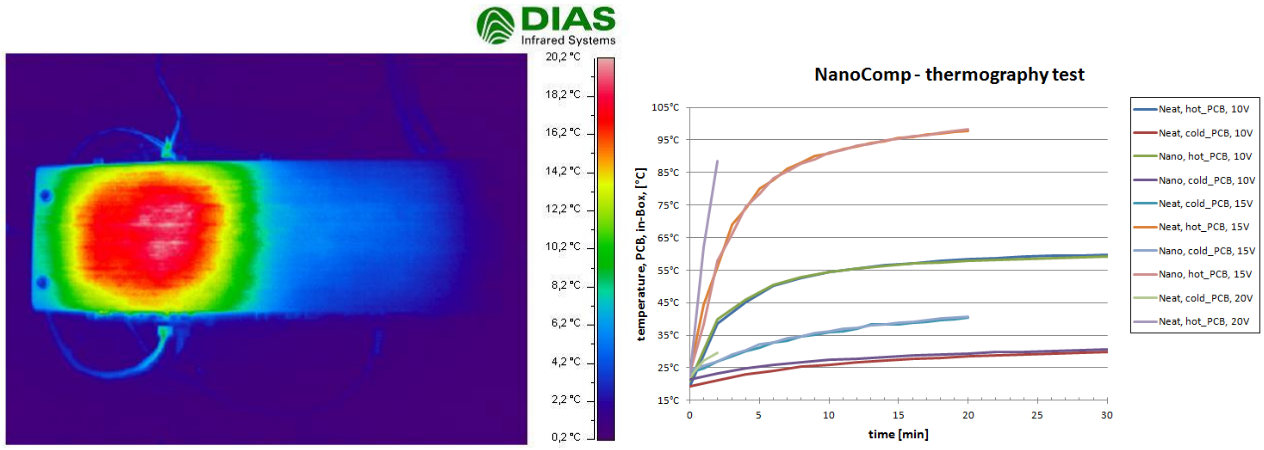

Figure 4-6: Infrared image, showing the temperature difference at the top of the box.
Nano-enabled Box. U = 15 V, t = 19 min
Right: Summary of the internal PCB temperatures during the tests.

The thermal vacuum test with the reference- and the NanoCOMP-Box shows differences in the resulting temperatures. However these differences are not as significant as expected. The maximum temperature at the top cover of the nano-enabled box is up to 7 % lower compared with the temperature at the reference box during heat-up and lower during cool down. Which means that the thermal conductivity of the nano-enabled box is better.

5 CONCLUSION AND WAY FORWARD

In this ESA GSTP activity the effect of nano-enabling of CFRP has been investigated. During an extensive sample test campaign basic material properties have been tested and compared with reference material. Additionally a pilot test application has been designed, built and tested in regard of potential benefiting properties.

Basic mechanical properties and the electrical conductivity of the ne-CFRP and the reference CFRP material have been tested on sample level. Thermal conductivity- and electro-magnetic attenuation tests have been performed on sample and on demonstrator level.

In terms of basic mechanical properties, it can generalized said that the nano-enabled material has a lower material strength, especially considering the 0° fibre direction.

The electrical properties have been changed due to a nano-enabling as well. The surface conductivity is increasing but the volume conductivity is decreasing significantly.

It has been shown that the thermal performance of CFRP-material can be improved significantly using nano-enabling. Within the demonstrator tests it was possible to show a small decrease of the temperature of the used power PCBs, due to improved conductivity and thus dissipation. However, the bottle neck in conductivity is the connection of the PCBs to the structure and the adhesive used there. Nano-enabling of the adhesive together with using metal-core PCBs might increase the performance in this application even further.

The electro-magnetically attenuation has been tested on sample and on demonstrator level. The basic material test shows good results. However these results could not be proofed with the demonstrator tests. It seems as if the imperfect geometry of the demonstrator parts lead to small gaps which reduce the shielding in several frequencies to zero.

However regarding the results of thermal conductivity and electro-magnetically attenuation it can be concluded that the nano-enabling has as significant effect, which is unlikely to be caused by the lower fibre-volume fraction.

It has been shown that nano-enabling has big potential to improve special material properties like thermal conductivity and electro-magnetically attenuation. Especially the latter properties have been a central design driver to use metal as standard materials whenever EM-attenuation or high thermal conductivity is necessary. With the new ne-process and the obtained material properties it is possible to replace a large amount of heavy metal parts with enhanced lightweight CFRP structures. Once space qualified and proofed by precursor missions the new developed material could be a game-changer in terms of weigh-saving for space missions.

The next logical steps regarding nano-enabled CFRP (ne-CFRP) are the following:

- Improve the manufacturing and processability of the ne-CFRP to reach equal material thickness and an equal volume-fibre-fraction
- Search for more possible implementations of ne-CFRP as metal substitute to save weight in satellite systems
- Retest of the properties- and space qualification with new application demonstrators, e.g. Honeycomb-facesheets
- Implement the ne-CFRP in a pilot satellite mission to test the behaviour and raise the TRL
- Introduction to the market