NPL REPORT
ESTEC Contract
21669/08/NL/EM

Summary Report

Nanotechnology Survey

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SEPTEMBER 2010

ESTEC Contract 21669/08/NL/EM: ***Nanotechnology Survey***

Lead Contractor: National Physical Laboratory (NPL)

Sub-contractors: Institute of Nanotechnology (IoN)

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1. EXECUTIVE SUMMARY

The overall goal of this project was to assist ESA in assessing the potential benefits of nanomaterials, quantify some of the potential improvements and provide a way forward for their translation from academic research topic to validated space materials.

Compared to traditional materials, nanomaterials promise an unprecented degree of control of the material's structure, enabling improved performances, or the development of new breaktrough materials. While great progress has been made on engineering nanostructured materials, the degree of control that nanotechnology promises is not yet fully realised.

We have produced three technical notes:
TN1 [1] classified the many nanomaterial species – a summary of this is presented inSection 2. Also within TN1, the European Nanotechnology landscape was mapped and a database of European nanomaterial suppliers developed.

TN2 [2] reported on the actual improvements offered by nanotechnology and on the materials needs of the space industry. A round table was organized at ESTEC with the other consortium and other relevant participants. The Round Table gave each consortium a new perspective on the task and assisted in the preparation of TN3.

TN3[3] was the final technical note and

- Compared the possible improvements using Nanotechnology, to the actual expectations of the space community
- Ranked and prioritises the possible improvements. Some of the considerations included technical feasibility, chance of success, time needed for demonstration.
- Prepared a nanotechnology roadmap for space applications, which covers a period of 5 years and consolidate the existing MNT CTB dossier road-map for Nanotechnology

We have identified seven technologies, where nanotechnology can have a significant impact for space applications:

- Polymer based nanocomposite for structural applications
- Ceramic nanocomposites for harsh environment
- Nanomaterials with tailored thermal properties
- Electro-conductive polymeric nanocomposites
- Nano-Thermoelectric materials for energy generation
- Advanced nano-coatings
- Improved energy storage

It was generally agreed that there is an immediate need for improved characterization techniques, which will lead to a better understanding of nanomaterials, better quality control of potential new materials and speed-up the adoption of potentially disruptive technology into the space sectors.

1. INTRODUCTION TO NANOTECHNOLOGY

Nanomaterials exhibit some outstanding functional characteristics based on a large surface-to-volume ratio and on quantum confinement effects. These new properties represent an opportunity for all sectors, particularly for space applications and missions because they address some important design constraints.

The key underpinning the nanomaterials "revolution" is the ability to understand and **engineer properties at a scale much smaller than ever before**. Compare to traditional materials science, nanotechnology and nanomaterials promise to offer a unprecented degree of control on the materials nanoscale structure. This in turn will open the door to more efficient materials or materials with new properties.

Major bottlenecks for nanomaterials large-scale adoption by the market is the need to develop reliable large-scale production processes for raw materials, controllable manufacturing techniques for the finished end product and appropriate characterisation and modelling tools. In short, the degree of control on the nanostructure of the final product needs to be improved by validating new characterization and production tools. This is particularly relevant for the space industry, which requires high reliability, high performance products. A successful strategy to reduce the time to market and increase the success of the final product is to involve the end-user in the early orientation of the work.

The field of materials research was, and continues to be, one of the early adopters of nanotechnology, with applications ranging from high performance materials to 'everyday' objects such as functionalized surfaces for glass. The term 'Nanomaterials' relates to the manipulation of materials on the nanometer scale, where new properties can be observed and engineered – such as improved electrical conductivity and mechanical strength.

International agreement starts to emerge in the field with a number of efforts by standard bodies. NPL is a leading member of the ISO TC 229 Working Group, which recently agreed an international set of definitions for nanomaterials.

In the technical note 1: "Eureopean Nanotechnology Capabilities", the following was provided for each class of nanomaterials:

- A definition of the term (using ISO TC 229 where available)
- The measured properties of the nanomaterial
- The potential non-space domain applications
- The different fabrication techniques
- Where available, market data on each nanomaterial

Here is a summary of each of the nanomaterial classes – the full version can be found in Chapters 2 to 11 of TN1[1].

- ***Nanostructured materials***

Nanostructured or nanocrystalline materials are defined as materials whose structural elements— clusters, crystallites or molecules—have dimensions in the 1 to 100 nm range. The properties of nanostructured materials depend on their crystal/grain size, their arrangement and the individual properties of their elements.

- ***Nanoceramics***

Nanoceramics are extremely fine grain structure ceramics that rely on the use of nanopowders as starting materials. Many of the features of clay-based ceramics, which have been with us for millennia, are on the nanoscale. In more recent engineered nanoceramics, the scientific emphasis has been on improving performance, whereas the technical difficulties are related to the handling of nanoscale powders and grain growth during the sintering process.

- ***Nanocomposites***

Nanocomposites are materials that are created by introducing nanoscale objects (the filler) into a macroscopic sample material (the matrix). Nanocomposites have been shown to exhibit exceptional properties or can combine different properties in a single material [4]. Adding CNTs to a polymer matrix could potentially enhance the mechanical properties, such as stiffness and strength [5], as well as modify the electrical and thermal properties of the material [6].

- ***Nanotubes***

An ideal carbon nanotube is a cylindrical structure based on the hexagonal lattice of carbon atoms that forms graphene. This network of carbon atoms rolled up to make a seamless cylindrical structure. This cylinder can be less than 5 nanometers in diameter, but can be tens of micrometers long. They have been observed in two forms - single-walled- or multi-walled (which includes double-walled).

- ***Nanoparticles***

Nanoparticles are nano-objects with all three external dimensions in the nanoscale [6.1]. Nanoparticles exhibit interesting properties based on specific characteristics (size, distribution, orientation, morphology, phase, etc.), when compared to the larger particles of the same bulk material. Confinement of electron in a nanoparticles also confer them useful electrical or optical properties

- ***Nanofibres for reinforcement***

Nanofibres are nano-objects with two similar external dimensions in the nanoscale and the third dimension significantly larger. [7] Nanofibres are flexible fibres a few microns in lengths and between a few nanometers to 100 nm in width. Just like nanowires, they can be fabricated from a wide range of materials, including metals, polymers and carbon. Nanofibres do not have the same regular structure of CNTs and so do not offer the same exceptional transport properties. They are most often used as reinforcement.

- ***Nanoclays***

Nanoclays are raw materials - nanoscale layered aluminum silicate platelets. Clays have a layered structure consisting of 2 types of sheets; silica tetrahedral and alumina octahedral sheets. The platelets are 1 nanometer thick and 70 – 150 nanometers across. Stacking of the layers leads to a regular Van der Waals gap between them called the interlayer or gallery.

- ***Fullerenes***

A fullerene is a molecule composed solely of an even number (between 60 and 100) of carbon atoms, which form a closed cage-like fused-ring polycyclic system with twelve five-membered rings and the rest six-membered rings [8]. Fullerenes are a family of molecules composed entirely of carbon, in the form of a hollow sphere, ellipsoid, tube, or plane. Spherical fullerenes are called buckyballs.

- ***Electronic Nanowires***

Nanowires can be defined as elongated structure with only two dimensions in the nanoscale and with properties that allow for the transmission of energy [9]. Many types of nanowires have been produced, including Ni, Pt, Au, Si, InP, GaN and SiO_2, TiO_2. Just like with CNT, quantum effects dominate nanowire applications, and as so, are often known as quantum wires.

- ***Quantum Dots***

Quantum dots (QD) are inorganic semiconductor nanometer-scale crystals. Their small size results in new material properties and new quantum phenomena, which arise from the confinement of electrons in thematerial. In a quantum dot, the electrons are confined in all three dimensions to a length scale of the order of the electron Fermi wavelength.

- ***Dendrimers***

A dendrimer is a macromolecule with a highly branched 3D structure. This structure provides a high degree of surface functionality. A dendrimer is always built up around a central multi-functional *core molecule*. Some hyperbranched polymers have similar structure to that of dendrimers, but with one difference – each unit within a dendrimer allows further branching.

2. MAPPING AND DATABASE

There are a number of key challenges facing the nanotechnology industry – the key one being a full understanding of the relationship between structure and properties at the nanoscale. There is also a great deal of hype about nanotechnology. However, various scientific and business communities are willing to stake their money because of the immense potential offered by nanotechnology.

The potential of nanotechnology was recognised in Europe at a relatively early stage. In the 1990s, several European countries (including Germany, France, Netherlands and the UK) conducted national forecasting activities to identify priorities for technology policies. But although Europe led the way in many respects, it was largely in response to the National Nanotechnology Initiatives in the US that nanotechnology was selected for a strategic push in Europe.

Today, most European countries have Government-supported nanotechnology research and development (R&D) initiatives. Other countries without specific national nanotechnology initiatives often have relevant R&D embedded within other programmes (e.g. biotechnology, materials, and microtechnology).

The three European countries with notable nanomaterials capabilities are:

- **Germany** – strong chemical industry (e.g. nanoparticles, novel materials) means that there is a large amount of investment in nanomaterials research. Example: BASF, Bayer, etc
- **UK** – there is a large focus on Nanometrology (e.g. characterization, standards) and sensors, but fewer nanomaterials producers than France or Germany. However the materials focus is more on finished products _composite, allys, ceramics- than raw materials. Example: NPL, BAE, Airbus
- **France** – R&D focuses on microsystems and silicon technologies (e.g. sensors, microbatteries, nanodot memory systems). Example: CEA/LETI

The 2008 Nanoscale Materials and Markets report by Nanoposts [10] is one of many examples analysing nanoscale technology companies across the globe. Europe is leading the way in terms of company numbers with 1,100 in total.

A separate study by Defra [11] in 2006, shown in *Figure 3*, illustrates the global distribution of nanoscale technology companies in terms of materials manufacturers only. The nanoscale materials manufacturing industry is dominated by the US (49%) followed by EU countries excluding the UK (21%), and the rest of the world (21%).

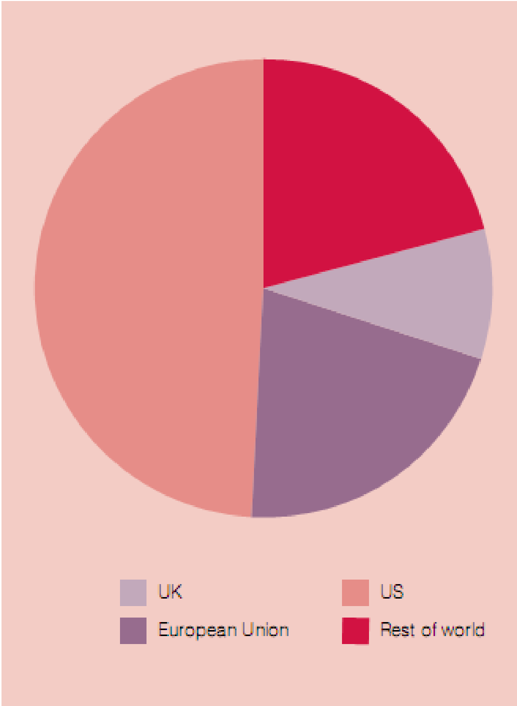


Figure 3: Geographical distribution of nanoscale technology companies manufacturing nanomaterials [8]

A database, correlating nanomaterials with different suppliers was produced. It also provided an indication of each suppliers size and developmental stage and, where possible, output and cost for different nanomaterials. A discussion of the current nanomaterials landscape in Europe was also produced, and gaps in the European market identified.

This analysis showed that nearly 200 different types of “off the shelf” nanomaterials are produced in Europe.

3. DEFINITION OF SPACE REQUIREMENTS

The first task was to identify the relevant space technologies where materials were considered important to enable their use. One aim of the task was to ensure that all potential areas of space technology were addressed and included a brief examination of the situation in other parts of the world.

The ESTER database contains the technology requirements identified by ESA across all space domains and so was considered a good basis for determining space technology priorities.

The review of current technology programmes involved an examination of the ESA TRP and GSTP programmes in order to identify specific technological objectives of ESA. Individual projects within these programmes are concerned with one or more of the requirements in the ESTER database. Consequently, they give an insight into how individual requirements are being addressed, and help in determining what role, if any, nanomaterials could play.

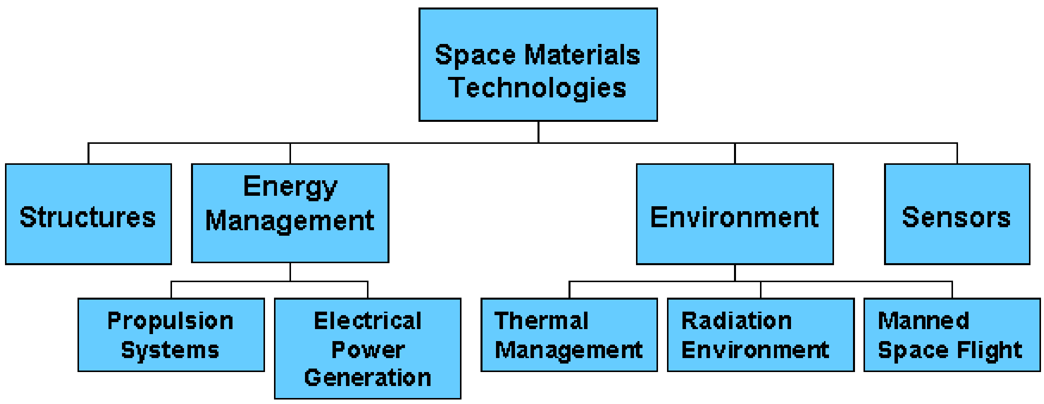
Nanotechnology activities make up only 3.6% of the TRP activities and it can be seen that these relate to sensors, electrical power generation or structures with nothing relating to propulsion systems, thermal management, manned space flight or radiation environment.

NASA has various activities relating to nanotechnology - many of these cover similar areas to the ESA TRP activities

In terms of materials technologies used for space, it is convenient to categorise them under four broad application headings:

- Structures
- Propulsion
- Electrical Power Generation
- Thermal Management
- Shielding
- Sensors

Full details given in Chapter 3 of TN2; “Nanotechnology and Space”



There are several areas of space technology where improvements in materials technology are needed and where nanotechnology could potentially be used. Many nanomaterials are at very early stages of development and are some way from being able to be used in space applications.

The key question to be answered at this stage **is whether nanomaterials can provide the improvements needed, and this requires emphasis on which properties of the material need to be improved.** This section looks at what improvements in the properties of materials are needed for the space technologies identified in the preceding sections and identifies those where the use of nanomaterials looks most promising.

3.1 Basis for the Investigation of the Improvements Nanomaterials can offer for Space Technology

Using the proposals discussed in previous sections, the following list has been prepared as the basis for the topics to be investigated as part of the investigation of the improvements that nanomaterials can offer for space technology:

- Mechanical properties of structures:
  - Young Modulus
  - Interfacial Strength
  - Stiffness
  - Fracture Toughness
- Thermal Management: properties which enable control of the thermal environment of the spacecraft and need to be improved:
  - Thermal capacity, e.g. heat storage;
  - Thermal conductivity including the ability to vary it;
  - Thermoelectric devices.
- Shielding and Coating:
  - Extended lifetimes, e.g. reusable thermal protection systems ;
  - Reduced mass;
  - Reduced cost;
  - Radiation shielding – electrically conductive nanomaterials
- Electric Power Generation:
  - Energy storage properties:
    - Improved energy density;
    - Increased lifetime
    - Improved efficiency of storage devices;
    - Increased power output over long or short periods.
  - Conversion system properties:
    - Conversion efficiency;
    - Improved power to mass ratio;
    - Reduced mass of the conversion system.
- Propulsion:
  - Improved propellant performance.

4. QUANTIFICATION OF POSSIBLE IMPROVEMENTS

This work package extensively reviews the possible improvements that nanotechnology may enable for space applications. We have reviewed the mechanical, thermal and electrical properties that can be enhanced by using nanocomposites or nanostructured materials, Where possible, we have also provided a best estimate of the quantitative improvement that can be expected, based on the latest published results or specification sheets of existing commercial products. Full details can be found in Chapters 1 – 5 of [2]

Mechanical Properties of Structures

One of the aims expressed in ESA CTB dossier is to use *"… new, lighter and more resistant materials*" [12]. Materials that offer more than one property, e.g. lightweight and thermally conductive, are of extreme interest to the aerospace industry.

Carbon nanotubes (CNT) reinforced nanocomposites have improved thermal and electrical properties while keeping mechanical performance such as Young's modulus, strain to failure and fracture toughness intact. The combination of conventional reinforcement fibres and carbon nanotubes has good potential for structural applications.

Thermal Management

There is a crucial need for the development of novel thermally conductive materials and structures. For example, for densely packed electronic devices dissipating high heat flux densities (~tens of W/cm^2), which also demand a very accurate temperature control (~ a tenth of a degree Kelvin).

Some carbon nanotubes have very high theoretical thermal conductivities of λ~6600 W/mK [13] along their length (and half the value across), at room temperature. This is twice that of a perfect heat conductor such as diamond. The thermal conductivity of CNTs is not only dependent on CNT diameter, radii and temperature, but also on CNT chirality: zigzag nanotube has the highest thermal conductivity and the chiral nanotubes have the lowest. CNTs therefore have the potential to provide materials with tuneable thermal conductivity.

Shielding and Coatings

The electrical characteristics of a material are directly related to its ability to shield from charge build-up, or even to shield from electromagnetic radiation in specific frequency ranges.

Some forms of CNTs displaying an electric-current-carrying capacity 1000 times higher than that of copper wires [13]. A low mass concentration of CNT could achieve conductivity similar to metals in a plastic epoxy composite. Carbon nanotube-enhanced plastics are used in electromagnetic interference/radio frequency interference (EMI/RFI) shielding and as anti-static materials [14].

Electrical Power Generation

One way to increase the available power from a battery and decrease the charging cycle is to increase the surface area of the active material. Nano-engineered materials or nano-coatings have been suggested as a means to do this. Nanomaterials are investigated to improve a a range of batteries properties:

- Energy storage properties
- Improved energy density
- Increased lifetime
- Improved efficiency of storage devices
- Increased power output over long or short periods
- Power performance of Solar Cells

Propulsion

Nano-powders of aluminium have been developed in recent years, and so far, have been the best characterised of all of the potential candidates. Reducing the physical size of the combustion product has been shown to improve their burning properties, as a larger surface area results in a larger burning surface.

5. ROUND TABLE

A round table table was organized at ESTEC and the conclusions were as follow:

- Repeatability and Reliability of processes for production is a key issue to be solved before nano can realise it's potential. Quality control issues with suppliers – good raw materials are needed
- There is also a need to have more trusted measurement and characterisation of nanomaterials. For example: standards on dispersion (in liquid or solid) are needed –
- Nano-enhanced thermoelectric generators or Peltier cells are also of interest. Thermoelectric could be good for specific missions (sun or outer planets) as generator or to cool specific sensors; need to start looking at it now

Priorities

- Reduce Mass
- Strength
- Electrical Conductivity
- Improved TPS
- Thermal conductivity
- Thermoelectric

Lower priority

- Batteries and solar cells
- Vacuum welding
- Combination / multifunctionality

6. COMPARISON, RANKING AND PRIORITISATION

Following the Round Table meeting between the consortium, ESA engineers and ESA suppliers, the initial list of materials properties was refined to include only areas and application considered to be highest priorities and larger impact for the space industry.

Seven broad materials properties (listed below with a few representative examples) were retained as potential areas where nanomaterials could offer real improvements. The notable addition is **Active Materials – thermoelectrics**. This was specifically cited at the Round Table as an area of potential interest to the space industry.

These areas were prioritised and the justification for the priority level is shown here:

Reduce Mass and improve strength (Structural Materials)

- **Priority Level**: *1 – 2*
- **Justification**: Composite materials are already used in the space industry, so there is an immediate need for the understanding and development of evaluation tests for the next generation of composites – nanocomposites.

Improved TPS (Thermal conductivity)

- **Priority Level**: *1 – 2*
- **Justification**: Work on nano-based TPS is already being carried out, so a fundamental understanding of the science behind the technology is needed alongside it.

Electromagnetic compatibility (Charging, Radiofrequency)

- **Priority Level**: *2*
- **Justification**: Advances in this area will add knowledge to the space industry, but before this, some non-space-specific work needs to be carried out, on the fundamentals of electrical conductivity across length scales (bulk versus nano)

Radiation Shielding

- **Priority Level**: *2*
- **Justification**: Traditionally, it had been assumed that materials with very low vacancy mobility are unable to self-heal and would thus be especially susceptible to damage. The existence of a nanomaterial self-healing mechanism means that such materials may be ripe for further investigation.

Active Materials (Thermoelectrics)

- **Priority Level**: *1 – 2*
- **Justification**: Thermoelectric materials can offer new power sources which do not need moving mechanical parts – efficient TE generators could change the way a satellite is powered, and only nanotechnology can improve their efficiencies

Coatings (barrier or re-enforcement)

- **Priority Level**: *1 – 2*
- **Justification**: Coatings are ubiquitous in space applications and can be further improved when scaled down to “nano”

Energy storage

- **Priority Level***: 2 – 3*
- **Justification***:* Some nanoparticles can drastically increase the power performance of conventional silicon solar cells, however, existing multijunction solar cells offer up to 40% efficiency, but may be more prone to degradation under irradiation. We believe there will be only small increase in efficiency from nano solar cells for the space industry. The main improvement could bring is financial one, a reduction in weight is also difficult to achieve.

Underpinning all of these activities is a need for reliable and repeatable measurement techniques, standards and validated data.

To achieve these goals, we have further broken down the problem in activities needed to develop a set of technologies, aiming to improve a given properties to enable new, more efficient or cheaper applications:

Activities ⇨ Technology ⇨ Improved properties ⇨ New applications

7. NANOMATERIALS ROADMAP

Action	Technology Description	Priority	Present	2011		2012		2013		2014		2015		2016	
NANO 1	Polymer based nanocomposite for structural applications		TRL 2	TRL 2	TRL 2	TRL 2	TRL 3	TRL 3	TRL 4	TRL 4	TRL 4	TRL 4	TRL 5	TRL 5	TRL 5
1.1	Industrialise dispersion of carbon nanotubes in polymer matrix	1													
1.2	Improve strength and toughness CNT-CFRP materials	1													
1.3	Validation of a structural model for nanocomposites	2													
NANO 2	Ceramic nanocomposites for harsh environment		TRL 1	TRL 1	TRL 2	TRL 2	TRL 2	TRL 2	TRL 2	TRL 3	TRL 3	TRL 3	TRL 3	TRL 4	TRL 4
2.1	Industrialise sintering techniques suitable for nanoceramic composites	1													
2.2	Improved toughness and wear resistance in nanoceramics composite	2													
2.3	Develop nanoceramics bonding on metal substrate	2													
2.4	Characterize fracture mechanism in nanoceramics and delamination in ceramics coating	2													
NANO 3	Improved thermal insulation using nanomaterials		TRL 1	TRL 1	TRL 1	TRL 2	TRL 2	TRL 3	TRL 3	TRL 3	TRL 4	TRL 4	TRL 4	TRL 5	TRL 5
3.1	Develop thermal insulation nanomaterials	1													
3.2	Design and produce nanocoatings for improved TPS	1													
NANO 4	Improved thermal transport in nanomaterials		TRL 1	TRL 1	TRL 1	TRL 2	TRL 2	TRL 3	TRL 3	TRL 3	TRL 4	TRL 4	TRL 4	TRL 5	TRL 5
4.1	Improved heat transport in carbon nanotubes / epoxy composites	1													
4.2	Develop anisotropic thermal transport materials	2													
NANO 5	Electro-conductive polymeric nanocomposite		TRL 1	TRL 1	TRL 1	TRL 1	TRL 2	TRL 2	TRL 2	TRL 2	TRL 3	TRL 3	TRL 3	TRL 4	TRL 4
5.1	Demonstrate reduced ESD sensitivity in polymer composite using nanofillers	2													
5.2	Extend CFRP processing techniques to produce highly RF conducting CNT/CNF materials	2													
5.3	Conductive nanocoating for ESD mitigation on satellite housing	1													
5.4	Improve bonding properties of coating on polymers	3													
NANO 6	Nano-Thermoelectric materials for energy generation		TRL 1	TRL 1	TRL 2	TRL 2	TRL 3	TRL 3	TRL 3	TRL 4	TRL 4	TRL 4	TRL 4	TRL 5	TRL 5
6.1	TE Materials Development activity	1													
6.2	Characterisation of Efficient nanostructured thermoelectrics	1													
6.3	Prototyping Ultra-high efficiency thermoelectric generator	1													
NANO 7	Improve radiation / EM shielding using nanomaterials		TRL 1	TRL 1	TRL 1	TRL 2	TRL 2	TRL 2	TRL 3	TRL 3	TRL 4	TRL 4	TRL 5	TRL 5	TRL 5
7.1	Characterize space radiation effects on nanocoating	1													
7.2	Improve radiation shielding efficiency of nanocoating	2													
NANO 8	Improve bonding properties of nanocoatings		TRL 1	TRL 1	TRL 1	TRL 2	TRL 2	TRL 2	TRL 3	TRL 3	TRL 4	TRL 4	TRL 5	TRL 5	TRL 5
8.1	Develop low friction surface coatings	2													
NANO 9	Improved energy storage		TRL 1	TRL 1	TRL 1	TRL 1	TRL 2	TRL 2	TRL 2	TRL 3	TRL 3	TRL 4	TRL 4	TRL 4	TRL 4
9.1	Develop reliable nanostructured electrodes for batteries	2													
9.2	Demonstrate high-power and increased lifetime for nano-enhanced batteries	2													
9.3	Characterize degradation mechanisms in nano-based supercapacitor	3													
NANO 10	Characterisation Techniques and fundamentals of nanomaterial		TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A	TRL N/A
10.1	Characterization of buried interfaces	2													
10.2	Validated tools to measure transport across interfaces	3													
10.3	Couple theory/modelling and experiment	2													
10.4	System integration - Understand and bridge multiple length scales	1													
10.5	Characterise Thermal transport at the nanoscale	1													
10.6	Test Thermal stress and characterise failure mode on nanomaterials	2													
10.7	Validated quality control methods for nanocoating	3													

General Activity Description

Each action (or technology) that has been listed in the roadmap has been fully expanded in General Activity Description (GAD). The following summarises the tasks required to provide the solution to each action.

NANO 1 Polymer based nanocomposite for structural applications

66 months TRL 2 – TRL 5

- 1.1: Industrialise dispersion of carbon nanotubes in polymer matrix
- 1.2: Improve strength and toughness of CNT-CFRP materials
- 1.3: Validation of a structural model for nanocomposites

NANO 2 Ceramic nanocomposites for harsh environment

54 months TRL 2 – TRL 3

- 2.1: Industrialise sintering techniques suitable for nanoceramics composites
- 2.2: Improved toughness and wear resistance in nanoceramics
- 2.3: Develop nanoceramics bonding on metal substrate
- 2.4: Characterize fracture mechanism in nanoceramics and delamination in ceramics coating

NANO 3 Improved thermal insulation using nanomaterials

48 months TRL 1 – TRL 4

- 3.1: Develop thermal insulation nanomaterials
- 3.2: Design and produce nanocoatings for improved TPS

NANO 4 Improved thermal transport in nanomaterials

42 months TRL 1 – TRL 3

- 4.1: Improved heat transport in carbon nanotubes / epoxy composites
- 4.2: Develop anisotropic thermal transport materials

NANO 5 Electro-conductive polymeric nanocomposite

54 months TRL 1 – TRL 3

- 5.1 Demonstrate reduced ESD sensitivity in polymer composite using nanofillers
- 5.2 Extend CFRP processing techniques to produce highly RF conducting CNT/CNF materials
- 5.3 Conductive nanocoating for ESD mitigation on satellite housing
- 5.4 Improve bonding properties of coating on polymers

NANO 6 Nano-Thermoelectric materials for energy generation

48 months TRL 1 – TRL 4

- 6.1: Thermoelectric Materials Development
- 6.2: Characterisation of efficient nanostructured thermoelectrics
- 6.3: Prototyping Efficient Thermoelectric Generator (TEG)

NANO 7 Improve shielding using nanomaterials

48 months TRL 1 – TRL 4

- 7.1 Characterize space radiation effects on radiation shielding efficiency of nanocoating
- 7.2 Improve radiation shielding efficiency of nanocoating

NANO 8 Improve bonding properties of nanocoatings
18 months TRL 3 – TRL 4
▪ 8.1: Develop low friction surface coatings

NANO 9 Improved energy storage
48 months TRL 1 – TRL 3
▪ 9.1: Develop reliable nanostructured electrodes for batteries
▪ 9.2: Demonstrate high-power and increased lifetime for nano-enhanced batteries
▪ 9.3: Characterize degradation mechanisms in nano-based supercapacitor

NANO 10 Characterisation Techniques and fundamentals of nanomaterials
54 months - TRL N/A
• 10.1 Characterization of buried interfaces
• 10.2 Validated tools to measure transport across interfaces
• 10.3 Couple theory/modelling and experiment
• 10.4 System integration - Understand and bridge multiple length scales
• 10.5 Characterise Thermal transport at the nanoscale
• 10.6 Test Thermal stress and characterise failure mode on nanomaterials
• 10.7 Validated quality control methods for nanocoating

Nano10 needs to be carried out in parallel with other activities – these will not further the TRL, but will allow for better understanding of the issues involved

8. CONCLUSION

Compared to traditional materials, nanomaterials promise an unprecented degree of control of the material's structure, enabling improved performances, or the development of new breaktrough materials. While great progress has been made on engineering nanostructured materials, the degree of control that nanotechnology promises is not yet fully realised.

There is an immediate need for improved characterization techniques, which will lead to a better understanding of nanomaterials.

This list of top priorities was assembled using the results from TN2; the feedback received from space industry experts at the Round Table and industry and academic literature. A top-level ESA-format roadmap has been prepared to show the TRL level for all of these priorities. An individual roadmap was also prepared for each area, which is connected to a General Activity Description (GAD).

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