

DRAFT NANOTECHNOLOGY ROADMAP

TECHNOLOGY AREA 10



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 10 input: Nanotechnology. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

Nanotechnology involves the manipulation of matter at the atomic level, where conventional physics breaks down, to impart new materials or devices with performance characteristics that far exceed those predicted for more orthodox approaches. For example, quantum confinement in nanoscale semiconductor particles, quantum dots, gives rise to novel optical behavior making it possible to tune the color of their fluorescence simply by changing their diameter. Nanoscale texturing of surfaces can allow for control of adhesion properties leading to biomimetic (Gecko-foot) self-healing adhesives and self-cleaning surfaces. The unusual combination of superior mechanical properties, electrical and thermal conductivity and electronic properties of carbon based nanostructured materials can enable the development of lightweight, multifunctional structures that will revolutionize the design of future aerospace systems. Nanotechnology can have a broad impact on NASA missions, with benefits principally in four areas.

Reduced Vehicle Mass

Replacement of conventional aerospace materials (composites and metals) with advanced composites derived from durable nanoporous matrixes and low density high strength and/or stiffness fibers can reduce aircraft and spacecraft component weight by one-third. Additional weight savings can be realized by replacing heavy copper wiring, which accounts for 4000 lb of weight on a Boeing 747 and about one-third of the weight of large satellites, with low density carbon nanotube wiring cables. Use of structural aerogel insulation in place of multilayer insulation (MLI) for cryotanks can eliminate the need for external foam insulation and the associated parasitic weight and production costs.

Improved Functionality and Durability

Nanoelectronic devices based upon graphene, carbon nanotubes, semiconductor nanowires, quantum dots/semiconductor nanocrystals and rods, are inherently more radiation and fault tolerant, have lower power requirements, higher speeds than conventional CMOS electronics. Integration of nanoelectronics and nanotechnology derived emission sources and detectors will lead to the development of advanced spectrometers and imagers that are one to two orders of magnitude lighter than conventional instrumentation, with twice the sensitivity and resolution and half the power requirements. Quantum structure enhanced solar

cells will enable the development of flexible, radiation tolerant solar cells with >50% efficiencies. These could be incorporated into the exterior of habitats and rovers providing for integrated power sources at reduced systems weight.


Enhanced Power Generation and Storage and Propulsion

Nanotechnology affords the possibility of creating high surface area materials with inherently higher surface activities and reactivity that could significantly enhance the performance of batteries and fuel cells and improve the handling characteristics of propellants. Use of nanostructured metal catalysts in PEM fuel cells could increase their energy density by 50%. Use of nanoporous materials and nanocomposites could enable the development of new batteries that could operate over a wide temperature range, from -100 to 100°C, to provide surface power for rovers and EVA suits. Nanoscale metal based propellants could replace cryogenic propellants and hypergolics leading to simplified storage, transfer and handling and reduced launch pad and in-space operational requirements.

Improved Astronaut Health Management

Nanoporous materials with tailored pore size and shape and surface chemistries will lead to the development of more efficient systems for the removal of carbon dioxide and other impurities from breathing air and organic and metallic impurities from drinking water. Distributed, autonomous state and chemical species detectors could find use in air and water quality monitoring systems, and in astronaut health monitoring. Nanofluidics based devices will enable the development of real-time, minimally invasive medical diagnostic systems to monitor astronaut health and aid in diagnosing and treating illness. Electrospun nanofibers with demonstrated potential to support tissue engineering and regenerative medicine can expand and radically change astronaut health management methods. Boron nitride or carbide based nanocomposites could be used as part of a habitat or rover structure, providing radiation shielding and MMOD protection.

A 20 year roadmap was created for the development and application of nanotechnology in NASA missions. This roadmap addresses mission needs as well as identifies nanotechnology that could lead to the benefits discussed above and enable radical changes in the way aircraft and spacecraft are designed and NASA missions are conducted. The roadmap is subdivided into four themes – Engi-



neered Materials and Structures, Energy Generation, Storage and Distribution, Propulsion, and Electronics, Sensors and Devices. Five Grand Challenges were identified that would enable the development of nanotechnologies with the most impact on NASA Missions. Increased investment in these areas will accelerate the technology development.

Development of scalable methods for the controlled synthesis (shape and morphology) and stabilization of nanopropellants.

High surface area and reactivity (metallic and inorganic) nanoparticle co-reactants or gelling agents can be used to develop alternatives to cryogenic fuels and hypergolics. Nanopropellants have the potential to be easier to handle and less toxic than conventional propellants, leading to simplified storage and transfer. A propellant comprised of nanoscale aluminum particle/ice slurry was recently demonstrated in tests by a team of researchers from Purdue and Penn State in a successful rocket launch. Technical issues that need to be addressed includes the development of passivation chemistries to control unwanted oxidation and the development of processing methods to tailor the shape, composition and morphology of these nanoparticles for controlled burning characteristics and methods to produce nanopropellants in large scales with good batch-to-batch consistency. NASA is currently partnering with other federal agencies in this area, but more work and investment is warranted.

Development of hierarchical systems integration tools across length scales (nano to micro).

High sensitivity and low power sensors (ppb to ppm level at μW - nW), high-speed (hundreds of GHz) electronics, and measurement enabling nanocomponents for miniature instruments are bound to interface with larger (micro, meso, and higher) systems to accomplish desired operation. System integration issues at that level can pose significant challenges and require the design of devices and processes that are suitable for both nano and microstructure fabrication schemes (chemical, thermal, and mechanical issues), structural integration techniques that are mechanically and thermally robust, and the development of efficient interconnects. In addition, a better understanding of factors that can degrade system performance, such as the effect of nano-micro-meso interfaces, packaging, and signal interference at component level, is needed along with effective mitigation strategies. NASA investments in meet-

ing these challenges can be leveraged with those of other federal agencies to accelerate developments in this area and address NASA specific needs.

Development of integrated energy generation, scavenging and harvesting technologies.

The use of quantum structures (dots and rods) to enhance absorption of solar energy and carbon nanotubes to improve charge transport and develop transparent electrodes will enable the development of flexible, radiation hard solar cells with greater than 50% efficiencies. Nanostructured electrode materials, self-assembled polymer electrolytes and nanocomposites will enable the development of new ultracapacitors with 5 times the energy density of today's devices and new, lighter and safer lithium batteries. Incorporation of flexible, conformal photovoltaics and improved efficiency, lightweight, flexible batteries into EVA suits and habitats would lead to enhanced power and reduced mass and enable longer duration EVA sorties and missions. Developments needed in this area include functionalization chemistries to allow incorporation of carbon nanotubes into devices, reliable, repeatable large scale manufacturing methods, as well as approaches to enhance radiation tolerance and nanoengineered coatings to prevent dust accumulation. An increased NASA investment in this area can be leveraged against ongoing efforts at Energy Frontier Research Centers as well as the upcoming NNI Solar Energy Signature Initiative.

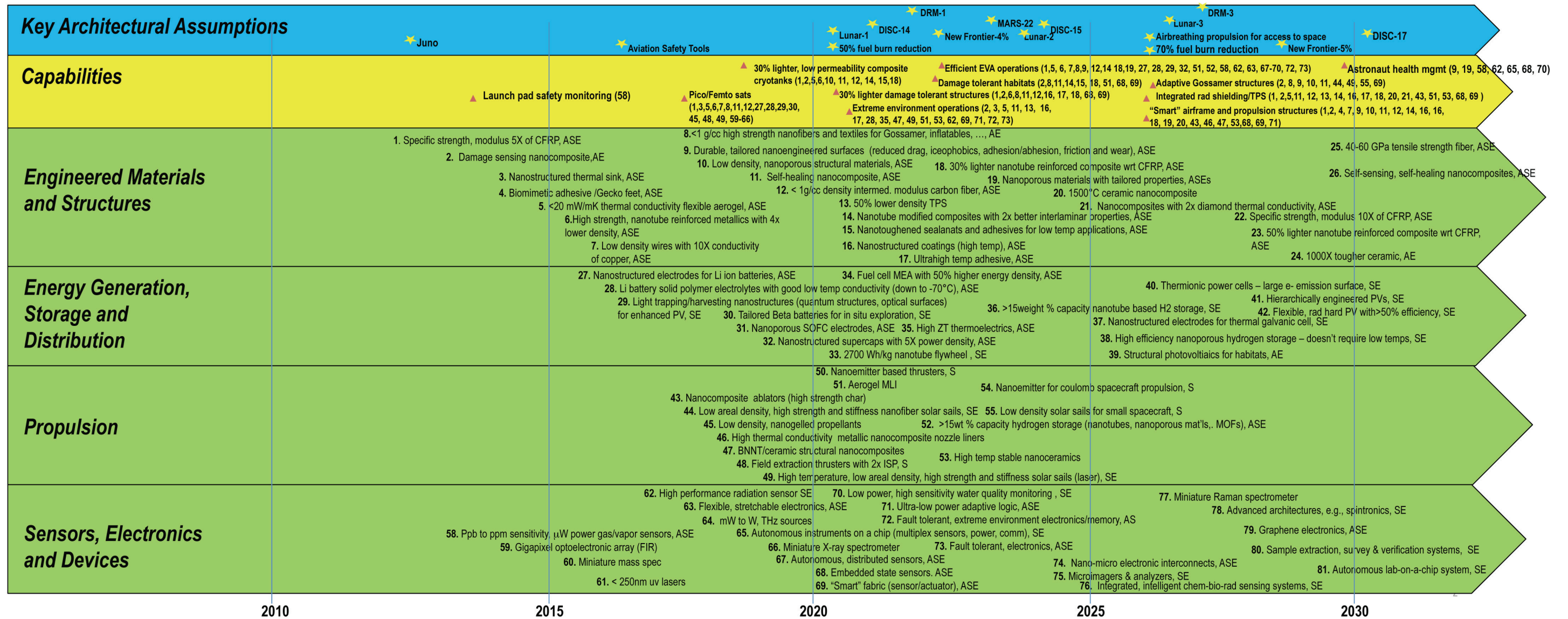
Development of nanostructured materials 50% lighter than conventional materials with equivalent or superior properties.

Carbon nanotube derived high strength and modulus, low density carbon fibers and lightweight, high strength and durability nanoporous polymers and hybrid materials will enable the development of advanced composites that would reduce the weight of aircraft and spacecraft by up to 30%. Technical challenges that need to be addressed include the development of reliable, low cost manufacturing methods to produce nanotubes, fibers and nanocomposites in large quantities and systematic studies to understand damage progression, degradation and long-term durability of these advanced composites to enable their efficient use in future aerospace vehicles. This technology area would be well suited for an NNI Signature Initiative that could be led by NASA.


Development of graphene based nanoelectronics.

Graphene based nanoelectronics can enable the

Figure R: Nanotechnology Technology Area Strategic Roadmap (TASR)



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development of radiation hard, high-speed devices, flexible electronic circuits, and transparent electrical conductors (a superior replacement for indium-tin-oxide coatings) that would find broad applications in NASA missions in exploration, science and aeronautics. Technical challenges that need to be addressed include the development of reliable, reproducible, and controlled methods to produce graphene on a large scale, a clear understanding of graphene and dielectric interfaces, device physics, foundry-conductive processes to produce large scale electronic circuits, and heterogeneous system integration issues. A concerted collaborative development supported within NASA and by other Federal agencies, including efforts in the planned NNI Nanoelectronics Signature Initiative, can realistically make graphene electronics a system of choice for avionics, extreme environment applications, an integral part of “smart” skin material (EVA suits), and for future probes and planetary landers by 2028-2032.

In addition to meeting NASA needs, these nanotechnology Grand Challenges can also help meet National needs in clean energy and National security. Advanced structural nanomaterials and nano-engineered coatings can be used to develop lightweight, more damage tolerant turbine blades for wind energy that are less susceptible to ice accretion and insect fouling. Advanced aerogel insulation can be used to improve the energy efficiency of homes and buildings. Nanotube electrical wiring can have a significant impact on reducing resistivity losses in electrical power transmission lines. Advanced photovoltaics, batteries and fuel cells can also meet needs for clean energy storage and generation. Nanoelectronics, sensors and actuators, and miniature instruments have wide use in many applications to meet other National needs. For example, nanosensors possess high sensitivity, low power and small size that can fit in a cell phone for extended coverage of sensing network for homeland security applications in detecting toxics and chemical threats. Such a cell phone sensor can be used in a clinic or at home for medical diagnosis and point of care health monitoring as well as by first responders for natural disasters and other accidents to determine the cause of incident and decide on the best approaches to solve it. Nanosensors can form a wired and/or wireless network that can be used to monitor the safety of a building or a stadium as well as for battlefield chemical profiling.

1. GENERAL OVERVIEW

1.1. Technical Approach

Nanotechnology involves the manipulation of matter at the atomic level where conventional physics breaks down to impart new materials or devices with performance characteristics that far exceed those predicted for more orthodox approaches. Quantum confinement in nanoscale semiconductor particles, quantum dots, gives rise to novel optical behavior making it possible to tune the color of their fluorescence simply by changing their diameter (Figure 1). Nanoscale texturing of surfaces can allow for control of adhesion properties leading to biomimetic (Gecko-foot) adhesives and self-cleaning surfaces (Figure 2). The combination of superior mechanical properties, electrical and thermal conductivity and electronic properties of carbon based nanostructured materials can revolutionize the design paradigm for lightweight multifunctional structures.

Nanotechnology can have a broad impact on NASA missions by enabling such advances as the development of ultralightweight, multifunctional materials for aircraft and spacecraft, robust fault tolerant electronics, high sensitivity, low power sensors for planetary exploration and high thrust propellants.

This roadmap addresses a 20- year plan for the development and implementation of nanotechnologies for NASA missions. The roadmap is organized into four themes – Engineered Materials and Structures, Energy Generation and Storage, Electronics, Sensors and Devices and Propulsion. Separate roadmaps for each Mission Directorate were developed that show how nanotechnologies developed in each theme can lead to new capabilities to support planned missions or enable new missions. From these separate roadmaps, cross-cutting technologies, i.e., those that are important to more than one Mission Directorate, were

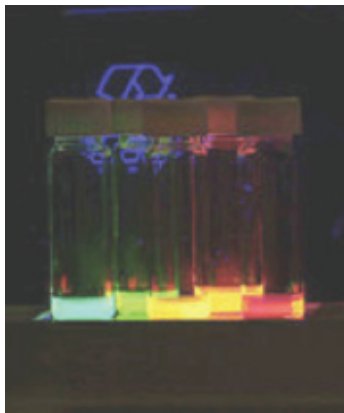


Figure 1. Size dependent fluorescence of quantum dots.

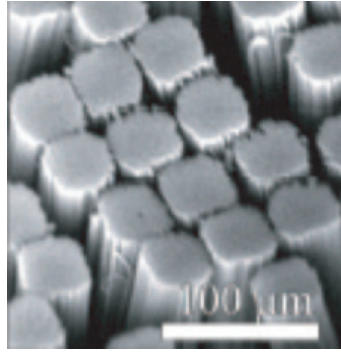


Figure 2. Carbon nanotube Gecko-foot adhesive (P.M.Ajayan, Rice University)

identified as potential candidates for further development along with selected mission critical technologies, such as those related to astronaut health management or miniaturized instrumentation for planetary exploration. Technical challenges were identified that enable the development of these technologies and are also presented in this document. In addition, five Grand Challenges are highlighted that, if successfully addressed, would revolutionize NASA's missions and the aerospace industry as well as have significant impact on meeting National needs, such as clean energy and homeland security. Investments by other Federal agencies that could be leveraged to help tackle these Grand Challenges were also identified.

1.2. Benefits

Nanotechnology can have a broad impact on NASA missions and programs in aeronautics, planetary science, and exploration.

Reduced Vehicle Mass

Replacement of conventional aerospace materials (composites and metals) with advanced composites derived from durable nanoporous matrixes and low density high strength and/or stiffness fibers can reduce aircraft and spacecraft component weight by one-third. Additional weight savings can be realized by replacing heavy copper wiring, which accounts for 4000 lb of weight on a Boeing 747 and about one-third of the weight of large satellites, with low density carbon nanotube wiring cables. Use of structural aerogel insulation in place of multilayer insulation (MLI) for cryotanks can eliminate the need for external foam insulation and the associated parasitic weight and production costs.

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1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, DRAs

While mostly a “push” technology, nanotechnology can have an impact on planned NASA missions. Carbon nanotube based nanocomposite struts and an engine cover plate will be flying on the upcoming Juno mission. Exploration missions will require lightweight materials for launch vehicles and cryogenic propellant tanks, as well as improved energy storage and generation. In addition to lighter weight structures and improved energy generation and storage, future science missions will need lightweight, compact, low power science instruments. Advanced aircraft currently being planned in the Fundamental Aeronautics Technology program will rely upon the development of lightweight, multifunctional materials for airframe components and durable, high temperature materials for advanced engine designs. “More electric aircraft” concepts will need improved power generation, storage and distribution. Each of these needs could be met through the application of nanotechnology.

1.4. Top Technical Challenges

The top technology challenges are provided in below:

Present to 2016

- Scale-able methods for the controlled synthesis (shape and morphology) and stabilization of nanopropellants
- Development of long-life, reliable emission sources for detectors and instruments
- Development of characterization tools and methodologies to measure coupled properties of nanostructured materials, including non-destructive and in situ methods
- Development of methods and knowledge-base to optimize bulk properties of nanostructured materials

2017 to 2022

- Development of manufacturing methods, including self-assembly based net shape fabrication, to produce nanoscale materials and devices on large scales with controlled structure, morphology and quality
- Development of hierarchical systems integration tools across length scales (nano to micro)
- Development of integrated energy generation, scavenging and harvesting technologies

2023 to 2028

- Development of nanostructured materials that

are 50% lighter than conventional materials with equivalent or superior properties

- Development of high fidelity and reliability multi-scale models to predict the properties of nanoscale materials and efficiently translate these properties into the design of new devices and structures
- Development of graphene based electronics

Beyond 2028

- Development of high specificity, single molecule detection methods

2. DETAILED PORTFOLIO DISCUSSION

2.1. Summary Description

The Nanotechnology Roadmap is broken down into four major themes – Engineered Materials and Structures, Energy Generation and Storage, Propulsion and Electronics, Sensors and Devices (Figure 3). A description of each of these themes follows.

2.2. WBS Description

2.2.1. Engineered Materials

A detailed roadmap for the development of nanostructured materials is shown in Figure 4. The roadmap is broken down into five topics – Lightweight Structures, Damage Tolerant Sys-

tems, Coatings, Adhesives and Thermal Control and Protection. A more detailed description of each of these topics follows.

2.2.1.1. Lightweight Materials and Structures.

A comparison of the predicted specific strength and stiffness of single wall carbon nanotubes, SWNT, with measured properties of conventional carbon fiber reinforced composites, CFRP, and various aerospace materials is shown in Figure 5. While the ultimate goal of developing continuous single wall carbon nanotube fibers has yet to be realized, considerable research has been focused on the development of carbon nanotube fibers leading to the development of wet and dry spinning techniques to produce these fibers. Research at Nanocomp Technologies has led to the development of a vapor phase synthesis method to produce large quantities of carbon nanotubes (single and multiwall) which can be spun into fibers or processed into large sheets. However, the tensile strength and modulus of these fibers are far from predicted values. Wang and co-workers at Florida State University have developed post-processing techniques for carbon nanotube sheets to achieve composite strengths 30% higher than conventional epoxy based CFRPs. Further improvements in processing to align the nanotubes as well as methods to increase nanotube-nano-

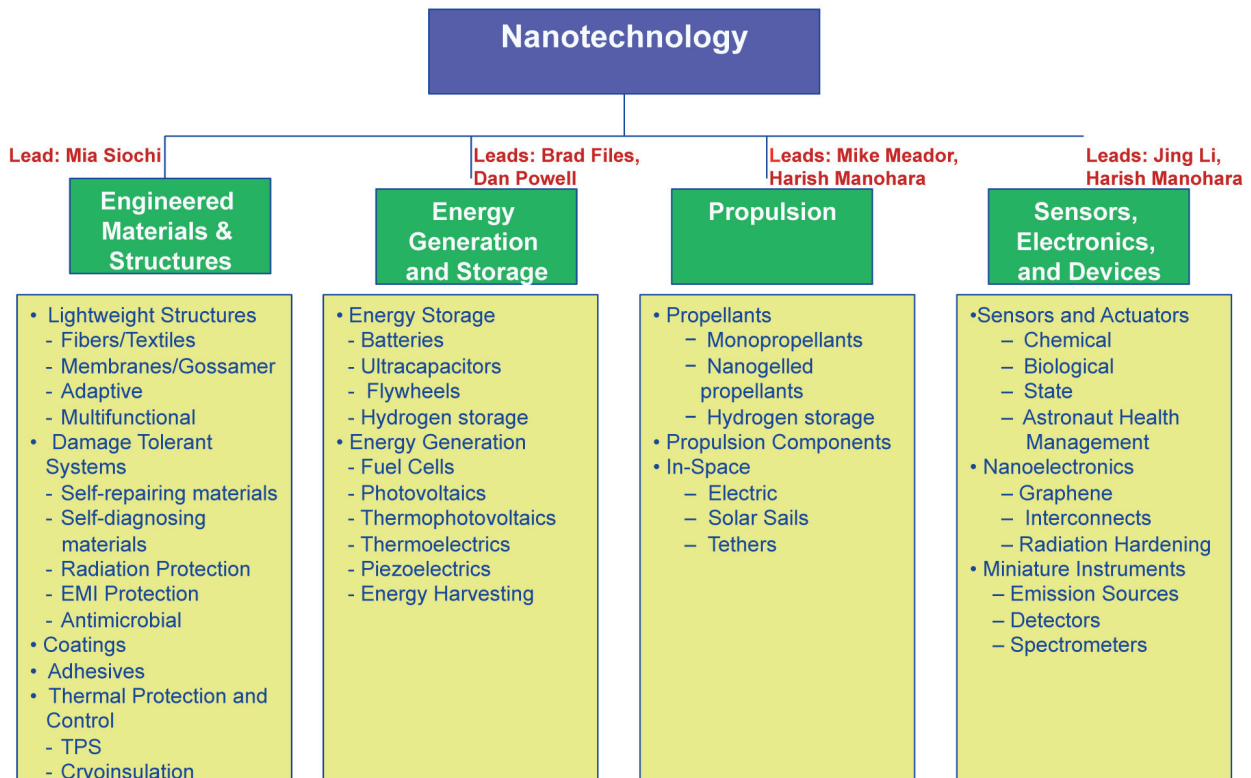


Figure 3. Technology Area Breakdown Structure for Nanotechnology

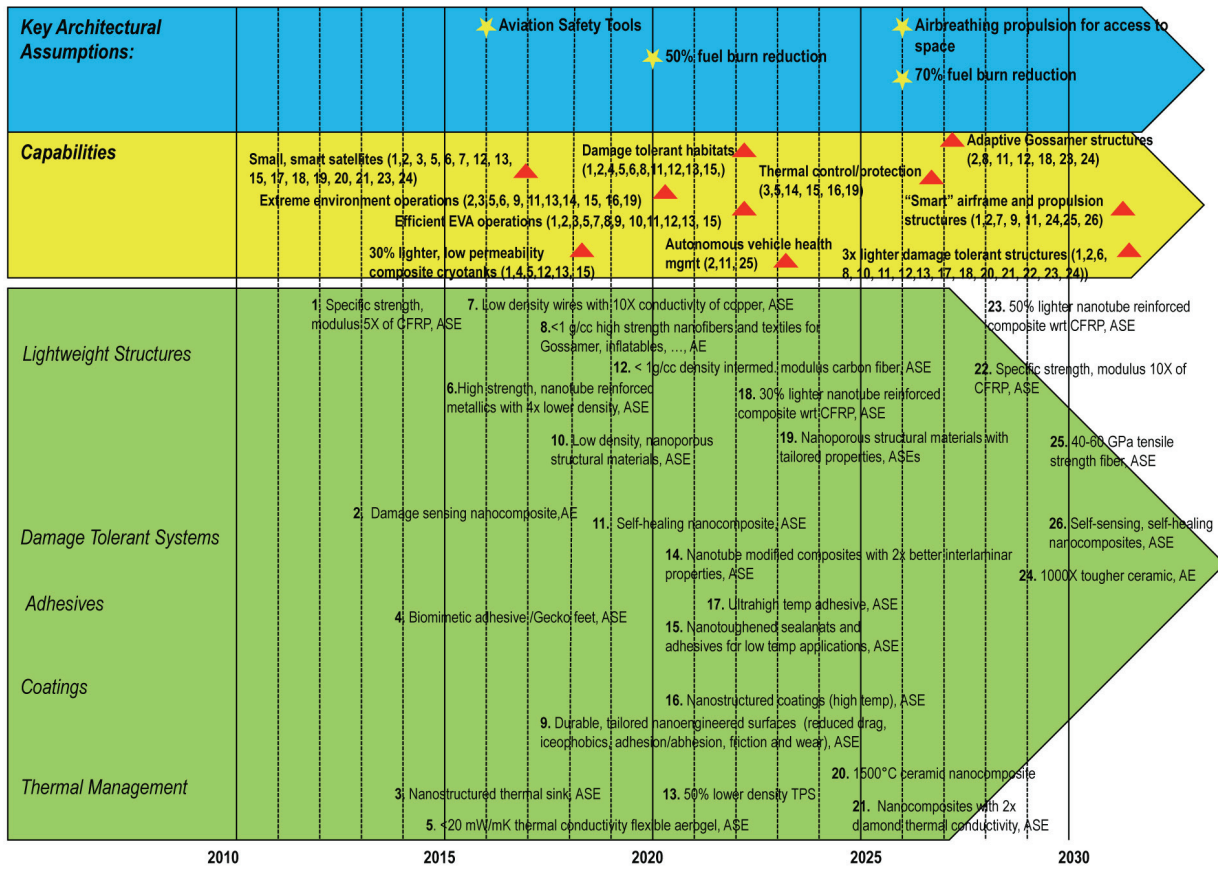


Figure 4. Engineered Materials and Structures Roadmap

tube interactions are expected to lead to SWNT based fibers with tensile strengths as high as 40-60 GPa by 2030. For example, research by Kumar at Georgia Tech has demonstrated that carbon fibers produced by carbonization of gel spun SWNT/polyacrylonitrile (PAN) nanocomposites can have tensile strengths 50% greater than carbon fibers produced from PAN. This improvement in tensile strength is attributed to the high degree of alignment of the nanotubes within the PAN fiber. Increases in tensile strength by a factor of two are projected by 2013 due to a high investment in this area by other federal agencies. Kumar has recently shown that it may be possible to use this approach to produce porous carbon fibers with properties equivalent to intermediate modulus carbon fibers but at one-half the density. With improvements in processing, including methods to produce these fibers in high volume with consistent quality, they should be at TRL 6 by 2019. Direct substitution of these fibers in place of conventional intermediate modulus carbon fibers should enable the development of 30% lighter carbon fiber reinforced polymer composites by 2022. Nanotechnology can also lead to significant improve-

ments in lightweight metals. Hierarchically nanostructured aluminum exhibited enhanced yield strength and elongation relative to conventionally engineered aluminum. Carbon nanotube reinforced aluminum nanocomposites had significantly greater hardness than unalloyed aluminum and tensile strengths approaching those of steel at a fraction of the mass.

2.2.1.2. Damage Tolerant Systems

Improvements in the durability and damage tolerance of polymers and composites have been realized through the addition of carbon nanotubes, graphene, and organically modified nanoclays. Miller has shown that addition of 5 weight percent clay to a commercial toughened epoxy leads to a two-fold increase in its notched Izod toughness. Recent work by Wardle at MIT and others has demonstrated that use of "fuzzy fibers", produced by the growth of carbon nanotubes onto the surface of commercial carbon fibers, can lead to enhanced toughness and damage tolerance in composites. Some issues have been noted with the poor carbon nanotube/carbon fiber adhesion and further work on methods to deposit catalysts onto

the fiber surface and post processing methods is needed to address this. The development of robust “fuzzy fibers” should lead to a two-fold improvement in the interlaminar toughness of composites by 2020. Self-sensing and self-healing nanocomposites based upon nanotubes and self-assembled materials are also expected to be available by 2030. Increased toughness in ceramics has been realized using nanoscale features similar to those found in nacre, the material that comprises sea shells. Further development of this concept should make it possible to enhance the toughness of conventional ceramics by a factor of 1000 by 2030.

Inclusion of boron based nanomaterials such as boron nanotubes, boron nitride nanotubes or boron carbide nanoparticles into polyethylene or other high hydrogen content polymers can enhance their ballistic toughness and enable the development of multifunctional structural composites that provide enhanced radiation protection and micro-meteoroid impact damage tolerance. Current production of boron and boron nitride nanotubes is on the laboratory scale and investments in methods to scale up production as well as functionalization chemistries to improve the mechanical properties of boron nitride or carbide nanoparticles should enable the development of multifunctional radiation shielding materials by 2024.

Metamaterials possess both a negative refractive index and negative dielectric constant, enabling wavelength shifts in these systems making them useful for electromagnetic interference shielding. The ability to manipulate materials at the nanoscale will open the design space for material compositions that yield this unusual property. Integration of these materials into load bearing structures will impart magnetic properties and offer a mechanism for integrated vehicle health monitoring and damage repair.

2.2.1.3. Coatings

Nanocomposite coatings can extend the life of materials at high temperatures by providing a barrier to oxidation and can improve the wear resistance of materials. Nanotexturing of surfaces can significantly alter their activity and impart superhydrophobic characteristics, reduce drag or minimize the accretion of ice, dust, and insect contamination. Large scale texturing methods need to be developed and the long-term durability of these nanoscale features must be evaluated before these coatings can be utilized in NASA missions. This technology is expected to be mature by 2017.

2.2.1.4. Adhesives

Strong electrostatic forces (van der Waals’ forces) cause carbon nanotubes to agglomerate. These forces have been exploited to give rise to reversible adhesion, similar to that found on the feet of Gecko lizards. Nanotube arrays deposited onto various substrates and micro/nano features give rise to surfaces that have shear and normal adhesion to a variety of substrates. This characteristic could prevent catastrophic failure in climbing robots and could enable the development of self-healing adhesives. Methods to scale up surface engineering of nanoscale features onto large surfaces, as well as techniques to study their long-term durability are necessary to mature these adhesives to TRL 6.

Sealants and adhesives tend to harden and lose their flexibility at lower temperatures where their elastic properties are necessary for adhesion, sealing and durability. The toughening of polymers through the addition of nanoscale fillers is fairly well known and should be readily applicable to develop cryogenic sealants and adhesives by 2021. Adhesives that can tolerate temperatures in excess of 400°C are needed for propulsion structures and thermal protection systems. Addition of organically modified clays and other inorganic nanoparticles, such as POSS, have been shown to improve the oxidative stability of polymers. Inclusion of these fillers into conventional adhesives as well as using them as the building blocks for new adhesives should enable the development of ultra-high temperature adhesives by 2022.

2.2.1.5. Thermal Protection and Control

Enhancements in the thermal conductivity of materials, in particular polymers, have been shown through the addition of carbon nanotubes and graphene. Theoretical studies have indicated that incorporation of “fuzzy fibers” into polymer matrices can lead to enhanced through the thickness thermal conductivity of these materials. Nanostructured materials with compositions known to have high bulk thermal conductivity may provide a path for nanocomposites with thermal conductivities twice that of diamond by 2025. These nanocomposites could find application in lightweight radiators and heat exchangers for vehicles and habitats and could also be used for thermal management in electrical circuits and spacecraft busses. Control of thermal expansion in composites used in satellites and antennae is critical since thermally induced expansion and contraction of composite structures can lead to distor-

Grand Challenge – Reduce the Density of Composites by 50%

Replacement of conventional carbon fiber reinforced composites with advanced nanotechnology based composites that weigh half as much but have equivalent or better properties could reduce the dry weight of aircraft and spacecraft by more than 30%. Ijima's discovery of carbon nanotubes in 1991 opened up the promise of developing materials with 100 times the strength of steel at one-sixth the weight. Despite a considerable amount of research and progress in carbon nanotube based materials, this promise has yet to be realized.

A comparison of the specific strength and stiffness of carbon nanotubes with various aerospace materials is shown in Figure 5. The large gap between properties of carbon fiber reinforced polymer composites (CFRP) and single wall carbon nanotubes (SWNT) supports a focused investment in this game changing technology. Recent work by Kumar at Georgia Tech suggests that it is possible to develop nanotube reinforced porous carbon fibers with high strength and stiffness at one-half the density of intermediate modulus fibers. Use of these fibers as a direct replacement for conventional intermediate modulus fibers could reduce the density of composites by as much as 30%. High strength nanoporous polymers and polymer-inorganic hybrids have been developed by NASA that have densities less than half that of monolithic polymers and good compressive strength and stiffness. Use of these as in place of conventional polymer matrixes has the potential to further reduce composite density to one-half that of conventional composites. Alternative processing methods that produce nanocomposites with morphologies and interfaces tailored for optimum properties will enable further weight reductions.

Several technical challenges must be overcome – a better understanding of the effects of processing conditions on the alignment of nanoparticles in a given material must be gained in order to develop nanotube reinforced polymers and nanoporous polymers with optimized properties, this understanding will also enable the development of robust, repeatable manufacturing methods to produce these materials in large scale and with good batch to batch consistency. The damage tolerance of these materials must be assessed to determine the effects of nanoporosity on properties and durability. Robust multiscale modeling techniques capable of predicting material response and failure are needed as well as design tools to develop concepts that fully utilize the benefits of nanostructured materials. NASA investment in this area, leveraged with investments in carbon nanotube production and carbon fiber development by other Federal agencies and the new NNI Signature Initiative in Nanomanufacturing would accelerate the development of this technology and make the promise of ultralightweight, high strength materials a reality.

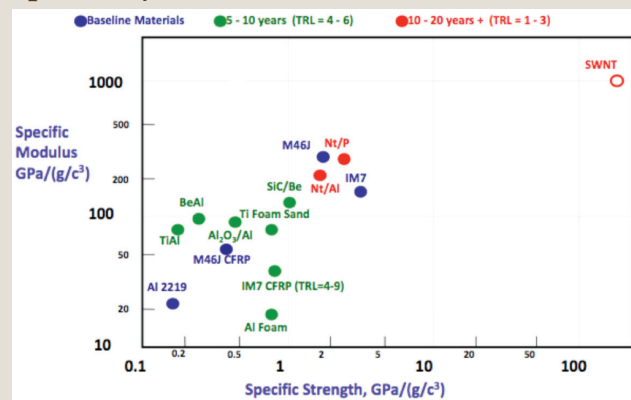


Figure 5. A comparison of the mechanical properties of SWNT with various aerospace materials.

tions that can negatively affect pointing accuracy. Addition of carbon nanotubes and graphene has also been shown to reduce the coefficient of thermal expansion in composites.

Char formation and stabilization is important for ablative materials used in rocket nozzles and thermal protection systems, since the char acts as thermal protection of the underlying ablative material. If the mechanical integrity of the char is poor, it can spall off and lead to high erosion rates for these materials. Reducing spallation or erosion of the char can enable use of less ablative materials thereby reducing nozzle or TPS weight. Addition of carbon nanotubes and nanofibers has been shown to improve the mechanical integrity of polymers and could be utilized to develop nanocomposite thermal protection systems that are half the weight of conventional carbon-phenolic ablators. Nanostructured carbides can provide

a path for lightweight, extreme temperature structural materials that can change the design space for thermal protection systems significantly, enabling structural concepts not available previously.

Flexible aerogels, either all polymer or polymer-inorganic hybrid, have been developed with thermal conductivities below 20 mW/m²K. These materials could find use as insulation in EVA suits, conformal insulation for cryotanks and habitats and as part of a multilayer insulation for inflatable decelerators for planetary entry, descent and landing. Current efforts to develop high volume methods to produce these materials as large area broadgoods will help mature this technology to TRL 6 by 2015.

2.2.1.6. Key Capabilities

Key capabilities enabled by developments in nanostructured are shown in the Table below.

2.2.2. Energy Generation and Storage

A detailed roadmap for the development of nanotechnology for energy generation, storage and distribution is shown in Figure 6. Because energy generation and energy storage rely heavily on processes that occur on the molecular level, it is not

surprising that there can be major advantages in using materials that are designed and built from the atomic level up. Some of the likely improvements will occur in applications such as batteries, fuel cells, ultracapacitors, photovoltaics, flywheels, energy harvesting, and energy distribution. There

Capability/Sub-Capability	Mission or Roadmap Enabled	Current State of Practice	Time to Develop
30% lighter, low permeability composite cryotanks: Enabled by low permeability, damage tolerant nanocomposites reinforced with high strength and stiffness carbon fibers and nanosheet fillers and by the use of durable, multifunctional polymer or polymer reinforced aerogels that can function as part of the tank structure.	Exploration, Science	Lightweight aluminum alloys or composites, multilayer insulation with sprayed on foam(as needed)	5-10 years
50% lighter damage tolerant structures: Enabled by high strength, high modulus fibers and concepts that take advantage of mechanical properties offered by: (1) nanostructured materials such as nanotube based fibers and nanoparticle toughened matrixes with 10X the specific strength over current materials, (2) approaches beyond substitution of conventional CFRP processing methods (3) ultralightweight, durable insulation materials such as aerogels or other nanoporous materials to reduce cryopropellant boil off, and (4) hierarchically nanostructured aluminum and nanotube/ aluminum composites for improved mechanical properties.	Human Exploration, Aeronautics, Air and Space vehicles	Carbon fiber reinforced polymeric composites, lightweight alloys	5 – 15 years
Extreme environment operations: Improved durability and operational capability of materials, structures, power systems and devices in extreme environments, including radiation, dust, high and low temperatures. Use of nanoscale additives, nanostructured coatings, self-assembly and self-healing to enhance durability at high and low temperatures; nanoengineered surfaces with tailored surface activity for dust mitigation; and nanoscale boron nitride/carbide and hydrogen filled nanostructures for radiation shielding. Nanoelectronics are inherently radiation resistant (small target cross-section) – or can be made radiation tolerant (tens of giga rads) without special processing/fabrication methods; vacuum nanoelectronics components are radiation insensitive and high temperature tolerant (>700 C). This also applies to sensors based on nanomaterials.	Human Exploration, Science, Aero Vehicles, Communications and Navigation	Si-Ge, SiC, and GaN electronics, FPGAs, radiation tolerant foundries; functional redundancy	6-10 yrs
Efficient EVA operations: Reduced mass (as much as 50%) and improved functionality of EVA suits through a combination of lightweight multifunctional materials (structure, radiation and MMOD protection, thermal insulation), lightweight energy storage, and energy harvesting/scavenging (conformal solar cells, piezo- and thermoelectric devices), and embedded sensors and actuators.	Life Support and Habitation	Suit construction includes durable fabrics, lightweight metals and composites. Batteries used for energy storage. Magnesium hydroxide canisters used for air purification.	10 years
Damage tolerant, multifunctional habitats: Reduced habitat mass, and enhanced damage tolerance, durability and functionality through the use of multifunctional structural materials (radiation and MMOD protection, thermal insulation), embedded nano-based distributed sensing (to locate the defect), electronics and logic (to determine the corrective action) and self-healing/actuation (to implement the corrective steps).	Life Support and Habitation	None	10-15 years
Adaptive Gossamer structures: Concepts for adaptive gossamer structures can be enabled by lightweight, high strength fibers with low creep to yield thin, compliant, reconfigurable and stowable structures. Nanoengineering to reduce membrane CTEs and raise specific heat is desirable. Embedded sensing for localized measurements of strain and temperature is required, as well as self-metallizing membranes for large gossamer structure reflectors. Tunable properties such as reflectivity, emissivity, absorptivity and CTE support system control to maximize momentum. High strength conductive fibers enable tethers supporting solar sail propulsion	Exploration, Science	IKAROS sail uses polyimide film and thin film solar cells. Size = 50 m	First use: 5-10 years, Full potential 15-20 years
Thermal Protection and Management: Reduce mass and improve effectiveness through: (1) 50% lighter TPS by precise nano-scale control of material pore sizes, thermal scattering sources for increased thermal resistance and mechanical properties; (2) durable, structural aerogel insulation with thermal conductivity < 20mW/m ² K; (3) lightweight radiators and thermal distribution systems using fibers 1-100 nm in diameter (e.g., carbon nanotubes, high temperature nanofibers, ceramics) with thermal conductivity as high as 2000 W/m ² K (> diamond)	Scientific Instruments, Sensors, Human Exploration systems, Robotic systems, Power and Propulsion systems, aeroshells (rigid and inflatable) for Entry, Descent and Landing	Carbon phenolic TPS, aluminum radiators and straps, heat pipes	First use: 5-10 yrs Full potential: 15-20 yrs
“Smart” airframe and propulsion structures: Reduced mass by taking advantage of inherent multifunctionality offered by nanomaterials to enable damage tolerant structural skin with embedded and distributed sensing permitting the detection and repair of cracks. “Smart skin” can respond to external stimuli such as aerodynamic loads and reconfigure to enhance laminar flow and reduce drag. Functionality such as vibration dampening can also be incorporated to enhance acoustic properties. Highly conductive skins can enhance damage tolerance to lightning strike damage.	N+3 SFW concepts, Launch Structures	Aluminum alloys and carbon fiber reinforced polymer composites. Sensors and wiring add significant parasitic weight.	First use: 10 yrs Full potential: 15-20 yrs
On-board Life Support Systems: Due to the high surface area and thermal conductivity, carbon nanostructures can be used as the next generation of surfaces for absorption and de-absorption of atmospheric constituents (e.g. CO ₂) for air revitalization. Additionally, engineered nano-particles can be used very effectively to remove contaminants from water and for recycling/recovery. Electrospun nanofibers for tissue engineering and regenerative medicine provide options for astronaut health management.	Human Health and Support Systems	None for long duration human space flight	5-10 yrs

is a strong need for future NASA missions to have enhanced energy storage methods, especially as missions become longer and more self-contained. High-efficiency power storage and distribution and thermal energy conversion for space power also become more important for future missions. These missions can be enhanced by utilizing power systems that minimize mass, improve reliability, and improve life capability to up to 10,000 hours.

2.2.2.1. Energy Generation

There are many examples of current nanotechnology projects related to advanced energy technologies. For example, nanotechnology is forming the basis of a new type of highly efficient photovoltaic cell that consists of quantum dots connected by carbon nanotubes. There could even be structural photovoltaic materials, where the structure of a habitat could also serve as a photovoltaic power generator. For solar energy, nanomaterials can make solar cells more efficient and more affordable. The efficiency of solar energy conversion and of fuel cells is expected to double.

Proton Exchange Membrane (PEM) fuel cells provide the promise for future specific power up

to 140 W/kg upon further work in the area of optimized catalyst chemistries, better materials, and better reliability. Nanotechnology promises to allow electrodes to provide greatly increased surface area and membranes with higher strength and lower ohmic resistance. This is believed to increase specific power past 800 W/kg.

Improvements in flexible, organic photovoltaics can be achieved through the use of carbon nanotubes to improve charge transport and quantum structures (dots and rods) to harvest more of the solar spectrum. These technologies are expected to lead to the development of conformal, radiation hard photovoltaic materials with efficiencies in excess of 50% by 2030. These improved solar cells could be incorporated into the outer structure of a habitat or rover and provide an additional source of power to charge on-board batteries.

2.2.2.2. Energy Storage

Using nanotechnology, future generations of energy systems can provide significant advances in terms of functionality, application and capacity. The weight of the Astronaut's Extravehicular Activity (EVA) suit could be reduced by 30%

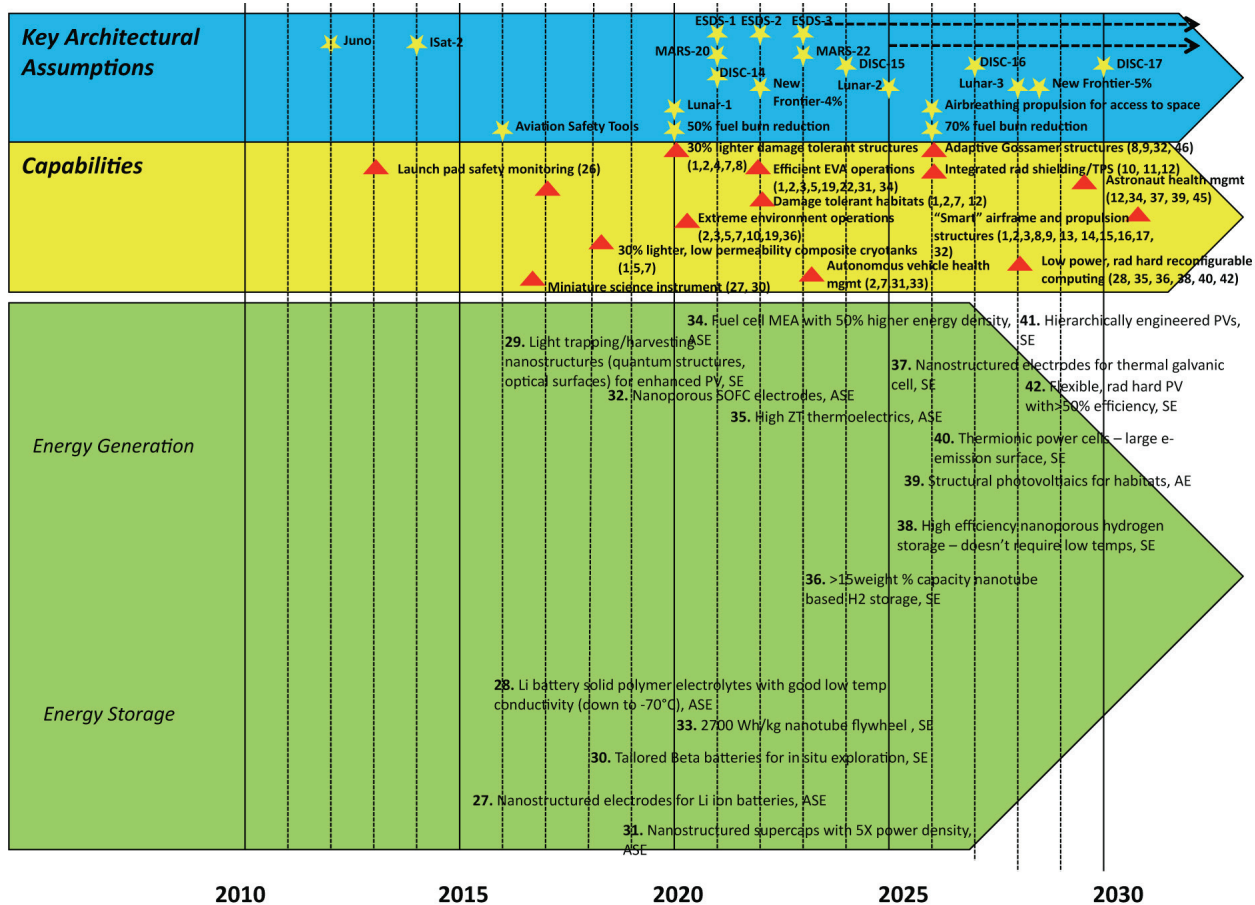
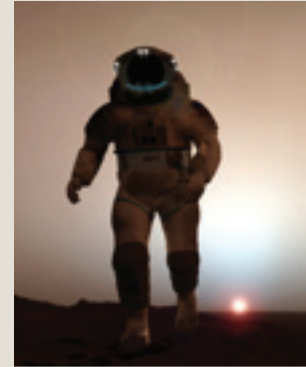


Figure 6. Detailed roadmap for energy generation, storage and distribution.

Grand Challenge - Structures with Integrated Energy Generation and Energy Storage (2017-2022)

Significant progress is currently being made in the areas of energy generation and energy storage using nanotechnology. The extremely high surface area and high reactivity of nanomaterials allows for power and energy densities far above that of conventional materials. One step forward in the field of energy related nanotechnology is to integrate multiple systems together allowing for an overall mass savings greater than each individual component could achieve on its own. The development of high efficiency organic/polymer photovoltaics would enable the production of conformal solar cells that could be incorporated into the exterior of a habitat or rover to provide auxiliary power. Developments needed in this area include functionalization chemistries to allow incorporation of carbon nanotubes into these devices to enhance energy transfer and their use in the development of flexible, transparent nanotube or graphene electrode materials. Incorporation of quantum dots or structures will lead to a broader use of the available solar spectrum. Methods to enhance the radiation tolerance of these devices and nanoengineered coatings to prevent dust accumulation are also needed. Flexible, safe lithium ion batteries could also be incorporated into EVA suit garments or habitats leading to significant weight savings. The development of new, flexible solid polymer electrolytes with the capability of operating at temperatures as low as -60°C could be enabled through the use of self-assembly processes, nanoporous polymers and nanoscale additives. Improvements in the electrochemical efficiencies of these batteries could be achieved through the development of high surface area electrode materials. The integration of both energy generation and subsequent energy storage allows for greatly reduced overall mass, helping to enable new long-duration missions that need additional power.



and the Personal Life Support System (PLSS) by 50% through the use of advanced, lightweight nanomaterials and lighter weight improved batteries. In the areas of fuel cells and photovoltaics, the prediction is to increase fuel cell MEA energy density and radiation hardened efficiency by 50% by 2015. Nanotechnology use in battery development for in situ exploration is expected to reduce overall weight by 30% within this decade. For batteries, high capacity bulk materials pose a critical challenge to long lifetime due to large volume changes to the host material as a result of Li insertion and extraction. The goal for supercapacitors or ultracapacitors with nanotechnology is to provide up to five times the power density of today's materials. In the near term, nanostructured electrodes are providing advances for lithium ion batteries.

2.2.2.3. Energy Distribution

Use of lightweight, low gauge carbon nanotube wire in place of conventional copper wire can significantly reduce the weight of power distribution systems in vehicles, habitats and EVA suits. In addition, nanotube wires do not corrode and are more ductile than copper thereby leading to more durable and safer wiring. Lightweight carbon nanotube wires and electrical cables have been demonstrated by Nanocomp. Testing the long-term durability of these cables, in particular under simulated space environments, are necessary to raise this technology to TRL 6 by 2016.

2.2.2.4. Key Capabilities

Key capabilities enabled by nanotechnology developments in energy generation, storage and distribution are shown in the Table below.

2.2.3. Propulsion

A detailed roadmap for the development of propulsion related nanotechnologies is shown in Figure 7. This theme is further subdivided into Nanopropellants, Propulsion Components and In-Space Propulsion. A discussion of each of these topics follows.

2.2.3.1. Nanopropellants

Depending upon their size and surface roughness, nanoscale particles can have surface areas in excess of 2000 m²/gram, roughly one-third the area of a football field. This high surface area gives rise to high surface reactivity, and the ability to adsorb large quantities of liquids or gasses. A research team at Purdue and Penn State has demonstrated that a slurry of nanoscale aluminum in ice provided enough thrust to propel a small rocket to a height of 1300 ft. Addition of nanoscale particles (metals and aerogels) has been shown to gel liquid hydrogen and hydrocarbon jet fuels. These nanopropellants have better handling characteristics than conventional cryogenic propellants and are less toxic than hypergolic fuels. However, in order for these materials to be suitable propellant replacements, passivation chemistries must be developed to prevent premature oxidation of the nanoparticles and synthesis methods, including self-assembly based techniques, are needed to

Capability/Sub-Capability	Mission or Roadmap Enabled	Current State of Practice	Time to Develop
Efficient EVA operations: See Lightweight Structures.	Life Support and Habitation		
Power/Energy Storage: Materials and devices for energy storage and power delivery depend significantly on the surface area available for charge transfer. Nano-scale materials (e.g. carbon nanotubes, nanorods) have >1000X greater areas than any conventional material: 50% more efficient proton exchange membrane fuel cells utilizing carbon nanotube and nanoparticle catalyst membrane electrode assemblies; lightweight carbon nanotube supercapacitors and battery electrodes for safer Li-polymer batteries.	Broad range of Exploration, Science missions	Nafion proton exchange membranes for fuel cells, Li-batteries (<100 Whr/kg)	First use: 5-10 yrs
50% Efficient, Low Cost, Flexible Photovoltaics: Photovoltaic arrays based on nanostructures for improved solar spectrum harvesting, e.g. quantum dot or quantum rod, and transparent carbon nanotube electrodes are predicted to have achievable efficiencies of about 50%. They are also expected to be as inexpensive and lightweight as thin film PV arrays are today.	Broad Exploration and Science Missions, High Altitude Long Endurance robotic aircraft.	Multi-junction arrays are approaching 30% (max <40%), thin film-arrays ~12% (potentially ~20%)	Full potential, 20 years.

tailor the shape and size of the nanoparticles in order to control burn rate (see Nanopropellant Grand Challenge). Nanostructured materials have also been investigated as a safe means for hydrogen storage. There is an active program in this area within the federal government with a goal of developing hydrogen storage materials with a sorption capacity of greater than 5.5 weight % by 2015 and an ultimate goal of greater than 8 weight %. One of the challenges that remain is to extend the temperature range at which absorption and desorption of hydrogen is the most efficient.

components can also be improved by the use of nanostructured materials. Recent NASA research has led to the development of new polymer/clay nanocomposites that have 60% lower permeability and better microcrack resistance than conventional toughened epoxies. Researchers at Michigan State have developed polymer/clay films with 1000 fold lower permeability. Multifunctional polymer reinforced silica aerogels have been developed that have thermal conductivities (<20 mW/m²K) and mechanical properties suitable for use as replacements for multi-layer insulation and would eliminate the need for external foam, currently used on the Shuttle Main Engine. Use of nanocomposites and aerogel insulation, along with

2.2.3.2. Propulsion Systems

The mass and performance of propulsion system

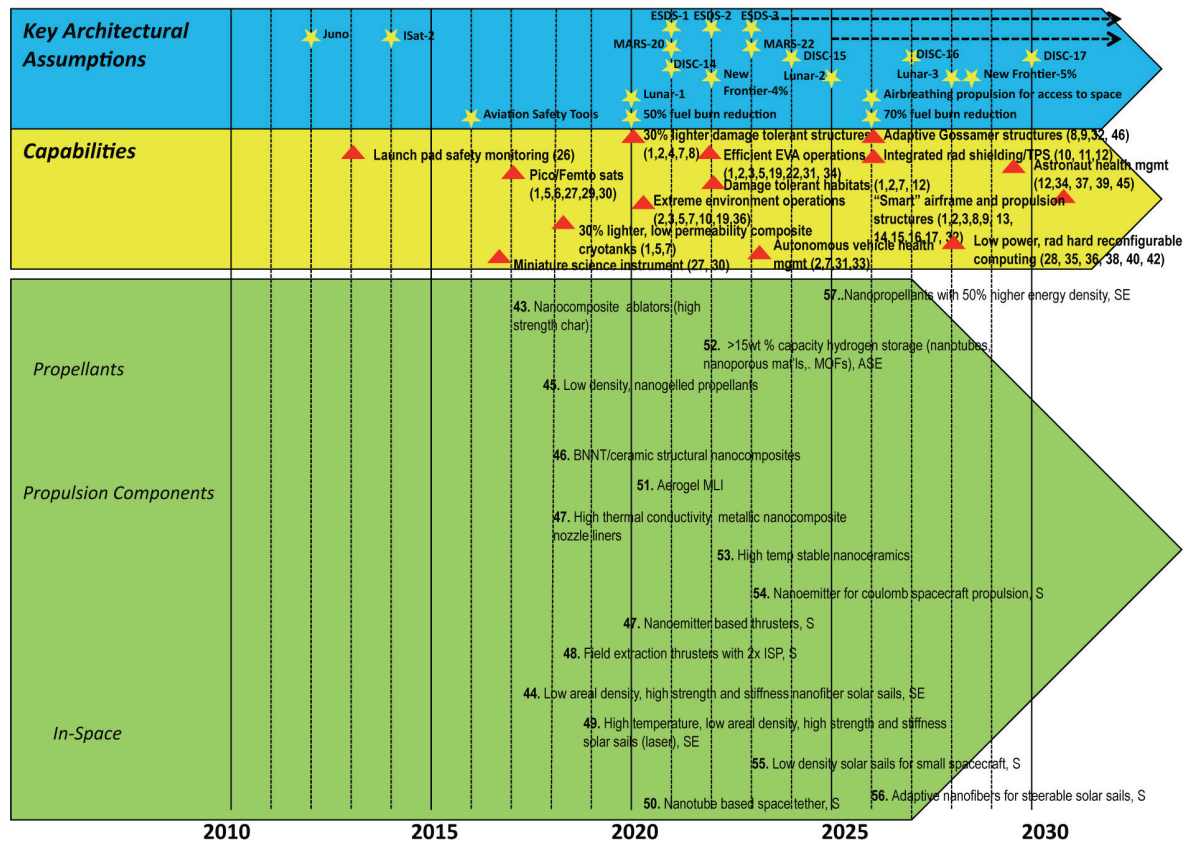


Figure 7. Detailed roadmap for the development of propulsion related technologies

Grand Challenge: Nanopropellants - From the Test Tube to Practice

Conventional cryogenic propellants present technical challenges in handling, storage and distribution. Cryogenic propellant tanks must be insulated often times resulting in the addition of parasitic weight to the vehicle. Long-term storage of cryopropellants also requires the use of cryo-coolers to limit boil-off which can also add weight to the vehicle. Compatibility and reactivity issues limit the materials that can be used for liquid oxygen storage and transfer. Currently available alternatives, such as hypergolics, are toxic and require special handling. Recent developments by a team of researchers at Penn State and Purdue Universities have demonstrated the feasibility of using nanoscale energetic materials, in this case a slurry of nanoscale aluminum particles in ice (ALICE), as propellants. In this first demonstration, a small ALICE powered rocket was able to reach a height of 1300 feet.

Significant technical challenges remain, however, before nanopropellants such as these can be used in NASA missions. Nanoscale metal particles are highly reactive materials. While this is desirable for propellants, it can create safety hazards. In addition, these particles are highly susceptible to surface oxidation which adds unneeded weight, as much as 20%, to the particles and reduces their specific thrust. Passivation techniques, such as functionalizing surface of the nanoparticles with organic groups can reduce susceptibility to oxidation and increase safety, however the proper functionalization chemistries must be identified that do not inhibit combustion. Manufacturing methods must be developed not only to scale up production of these materials, but also to develop ways to control the size and morphology of the nanoparticles and influence their burning behavior. Novel fabrication methods will enable the synthesis of core-shell nanoparticles with different metals in each layer of the nanoparticle which could be tailored to create particles with highly controlled burn rates and energies. Currently NASA is collaborating with other government agencies to mature this technology.



Figure 8. Photograph of an ALICE powered rocket prior to its successful flight on August 7, 2010 (S. Son, Purdue University).

new high performance carbon fibers is expected to enable the development of composite cryotanks that are 30% lighter and more damage tolerant than today's tanks.

Use of nanostructured materials in aircraft engines can improve their performance and durability. The high temperature stability of fiber reinforced polymer composites can be enhanced by as much as 25% through the addition of small amounts of nanoclays. This enables the development of fan and compressor components with better long-term durability. Conventional composites have recently been introduced into the fan containment system for the GENeX engine that is powering the Boeing 787, leading to weight reduction of over 300 lb per engine. Further reductions in containment system weight could be enabled by the use of advanced carbon fibers and tapes to develop composites with improved impact resistance. Improvements in engine performance could be achieved through the incorporation of "smart" adaptive composite materials in the inlet to tailor air flow and in adaptive fan blades with switchable pitch and camber. This technology, expected to be available by 2032, would require advances in low density, high strength composites as well as adaptive fibers and textiles. New concepts in turboelectric propulsion are being developed in which conventional aircraft engines

would be replaced with lightweight electric motors that are powered either by turbines or fuel cells. Such an approach would lead to significant noise reductions. High conductivity carbon nanotube wires with high current capacity, expected to be available by 2016, could enable the development of lightweight, high horsepower electric motors and could also be used in the wiring cables for power distribution. In order to mature this technology, scale-able methods for producing carbon nanotube wire with the right current carrying capacity must be developed. There has been good progress in this area. Nanocomp Technologies Inc. has developed a method to produce carbon nanotube wires and has demonstrated them in a small, lightweight electric motor to cool electrical components and has also developed nanotube based wiring cables.

2.2.3.3. In-Space Propulsion

Micropropulsion subsystems are critical to enabling small satellite capabilities in formation flying, precision pointing, proximity operations, drag-make-up, autonomous swarm operations, orbital (and de-orbital) maneuvers, and for general spacecraft attitude control. The key properties for a micropropulsion subsystem include its total wet mass and volume, min/max/avg power usage, and total impulse capability. For small satellites, especially for Femtosats (total mass 100 g), nano-

tips/tubes integrated electrospray arrays offer the performance, flexibility, and scalability for both fine-precision attitude control and highly efficient main delta-v propulsion from one compact subsystem. It is expected to provide I_{sp} of 500-5000 s, thrust levels of 10 to 100 μ N while consuming 1-2 W, and occupying a volume of < 10 cc. A fully mature development of this system is expected to be by 2020.

Solar sails can benefit from the development of ultralightweight, durable fibers, films and textiles. One approach to fabricating ultralightweight nanofibers and textiles that has been demonstrated is electrospinning. Incorporation of nanotubes or graphenes into these nanofibers would lead to enhanced strength, and improved durability and radiation resistance. Improvements in processing methodologies to better align the nanoparticles for more effective property translation and practical approaches for large scale manufacturing are needed to mature this nanofibers and textiles by 2017.

2.2.3.4. Key Capabilities

Key capabilities enabled by nanotechnology related developments in propulsion are in the Table below.

2.2.4. Electronics, Devices and Sensors

A detailed roadmap for electronics, devices and sensors is shown in Figure 9. This theme is further subdivided into Sensors and Actuators, Electronics and Miniature Instruments. A discussion of each of these topics follows.

2.2.4.1. Sensors and Actuators

Nano-scale sensors are highly tailorable and can achieve single-photon sensitivity and single-molecule detection while operating at μ W or nW levels. They can be made from a wide variety of nano-engineered segments of DNA and other biological molecules. They are also readily integrated with sensor electronics to produce very compact, highly “intelligent” instruments. The rate of progress in this area is very rapid. NASA successfully flew a Nano ChemSensor Unit on a US satellite in 2007. This NCSU, the first example of a nanotechnology based sensor system in space, was capable of

detecting trace amounts of nitrogen dioxide. In 2008, NASA flew a compact trace gas sensor system (the Electronic Nose) comprised of a main nanoparticle-impregnated polymer sensor and an auxiliary carbon nanotube-based chemical sensor on the International Space Station. It is anticipated that such sensor systems can achieve sensitivity in the ppb level with precise selectivity through the use of appropriate chemical functionalization.

The electrical behavior (conducting, semiconducting or insulating) of CNTs is dependent upon their structure (rolled configuration and diameter). Therefore creating the capabilities to control the structure or, alternatively, the ability to separate various types of CNTs is an interesting challenge. Recently NanoIntegris, a small business based in Skokie, IL, has developed a process to make 99% pure semiconducting SWNTs and 99% pure metallic SWNTs. These pure carbon nanotubes have been used by NASA to make an array based sensor system.

A suite of sensors for state sensing (temperature, pressure, humidity), autonomous distributed sensors for chemical sensing, biological sensing, water quality monitors for human and robotic exploration are expected to be available by 2020. One of the main developments required to be coupled with these sensor system is the sampling, sensor cleaning or replacement, and waste rejection schemes that make them autonomous systems. When integrated with nanoelectronics and embedded in “smart” materials, an intelligent chembio-rad sensing system is projected to be available by 2025.

2.2.4.2. Electronics

With recent advances in graphene, III-V nanowire technologies, and a deeper understanding of carbon nanotubes, a clearer path towards achieving less than 10 nm feature sizes and junction areas is projected by 2025. Such developments are expected to use either e-beam direct write or lithography-free, direct synthesis techniques. Graphene has shown great promise as the next generation electronics material with electron mobility of $\sim 200,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and is conducive for large area synthesis in tune with traditional found-

Capability/Sub-Capability	Mission or Roadmap Enabled	Current State of Practice	Time to Develop
Fully capable smart, small satellites (100 g) with formation flying capability for science and inspection: See Sensors, Electronics and Devices	Autonomous Systems, Distributed sensing, Large area aperturing, and Robotics	Limited capability kilogram-class spacecraft and aero vehicles with very limited capability	First use: 10-12 yrs
30% lighter, low permeability composite cryotanks: See Lightweight Structures			
Adaptive Gossamer structures: See Lightweight Structures	Exploration, Science	IKAROS sail uses polyimide film and thin film solar cells. Size = 50 m.	First use: 5-10 years, Full potential 15-20 years.

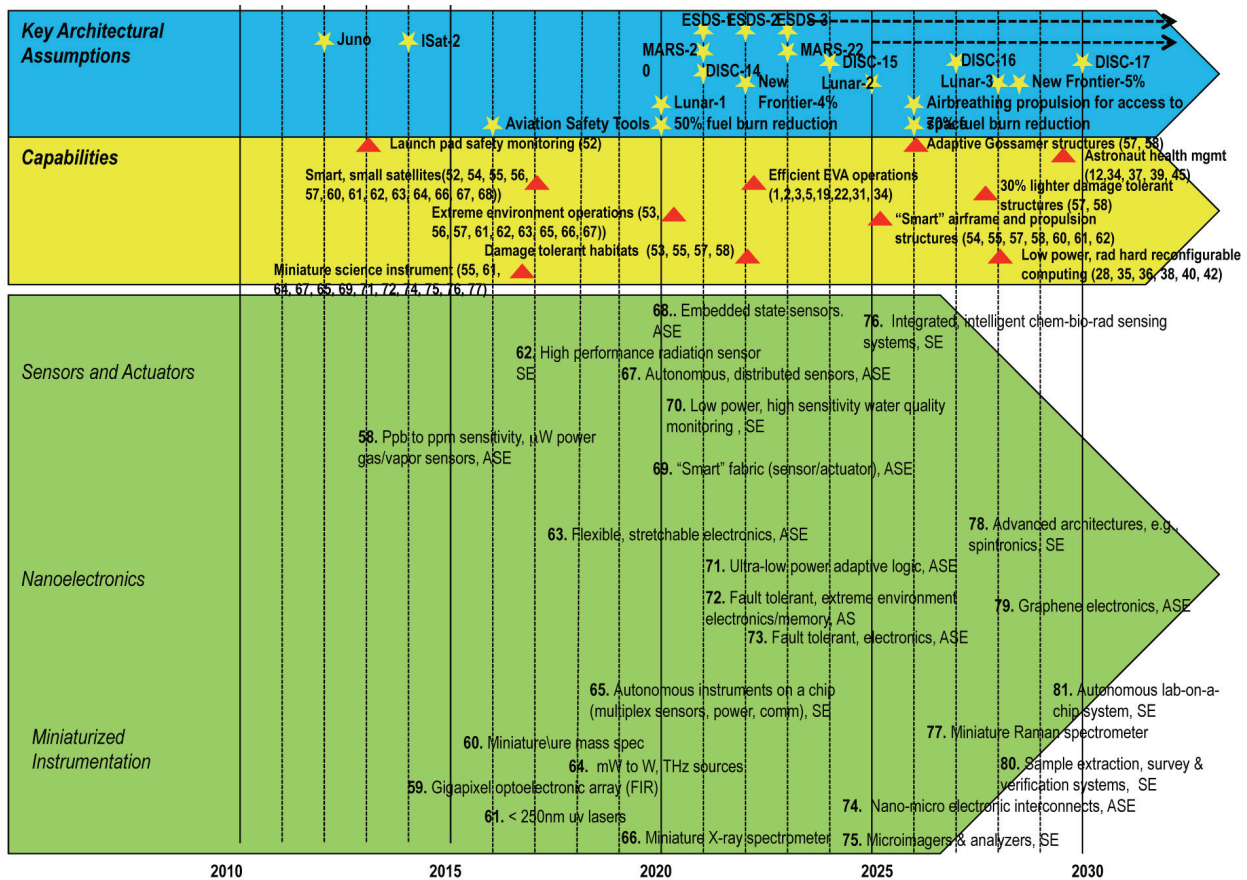


Figure 9. Detailed roadmap for electronics, devices and sensors.

ry processes. Recent demonstration of 300 GHz transistors using graphene supports projection of developing high speed devices that operate at THz levels by 2020 with potential to develop fully functional high speed circuits that can be employed in missions by 2028.

Both graphene and embedded nanowires allow development of flexible and stretchable electronics. Graphene with its breaking strength of 100 GPa and capability to be a single atomic thickness sheet offers extraordinary material choice to develop flexible, transparent electronics that potentially can shrink the entire avionics and system electronics volume by an order of magnitude. The high-light features of nanomaterial-based electronics is that in many cases they tend to be highly radiation resistant (due to their small target cross-section) – or can be made radiation tolerant (tens of giga rads) without special processing/fabrication methods. Additionally, a new class of vacuum nanoelectronics components demonstrated recently are both radiation insensitive and extremely high temperature tolerant (>700 °C) making them suitable for extreme environment applications. These devices use nanotubes or nanowires integrated

with microstructures and together with nanoelectronics should be available for fault-tolerant extreme environment electronics and memory applications between 2020 and 2025.

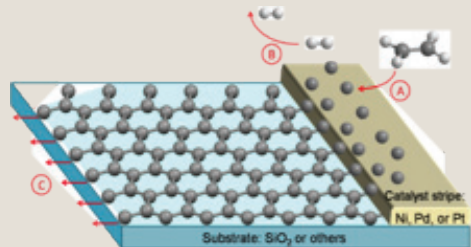
The above-mentioned materials help decrease device dimensions beyond what is directly possible using standard semiconductor processing techniques. As device dimensions approach that of an atom, the performance enhancement of these charge transport-based devices reaches a fundamental limit, referred to in the literature as “the end of the silicon roadmap”. A new approach, spintronics, utilizes electronic spin rather than charge to define logic states. While in its infancy, spintronics holds the promise of significantly enhanced performance over conventional architectures. Spintronics based devices are expected to make an impact sometime after 2025.

2.2.4.3. Miniature Instrumentation

These can be treated as payload subsystems whose mass can be decreased by one to two orders of magnitude, and performance in terms of measurement resolution, sensitivity, S/N ratio, power consumption can be enhanced by 2× to an order of magnitude using nanotechnology. High impact

Grand Challenge - Graphene Electronics: From Material to Circuits (2023-2028):

Graphene is a single layer (or 2 – 9 layers) sheet of carbon atoms with a single (0001) basal plane graphite structure. Graphene has shown great promise as the next generation electronic device because of its attractive properties such as: 1) the highest electron mobility ($\sim 200,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) and thermal conductivity ($\sim 4,000 \text{ Wm}^{-1} \text{ K}^{-1}$) of any material yet tested; 2) high flexibility with breaking strength near that of carbon nanotubes ($\sim 100 \text{ GPa}$), (3) low optical absorbance ($\sim 2\%$) in the visible region rendering it transparent conductor, and (5) small but tunable band gap in a two-layer form when electric field is applied orthogonal to the film plane. These properties enable the development of high-speed devices, flexible electronic circuits, and transparent electrical conductors (a superior replacement for indium-tin-oxide coatings). Single atomic thickness also renders graphene naturally radiation hard. A concerted collaborative development supported within NASA and by other Federal agencies can realistically make graphene electronics a system of choice for avionics, extreme environment applications, integral part of “smart” skin material (EVA suits), and for future probes and planetary landers by 2028-2032. To achieve this level of maturation, the necessary hurdles to overcome include: development of reliable, reproducible, and controlled graphene synthesis process on a large scale, clear understanding of graphene and dielectric interfaces, device physics, foundry-conductive processes to produce large scale electronic circuits, and heterogeneous system integration issues. The development of graphene-based devices is one of the topics being addressed in a 2011 NNI Signature Initiative in Nanoelectronics.



One of large area Graphene synthesis processes using metal catalysts. Adsorbed hydrocarbons are reduced to form condensed Graphene sheet.

developments include miniaturization of spectroscopic instruments for remote and in situ exploration. Development of high-current density (1 A/cm^2 to 100 A/cm^2) cold electron sources that can operate reliably for 1000s of hours with $<10\%$ degradation can enable the realization of photon sources at different wavelengths (e.g., X-ray, UV, THz, mm-Waves) for spectroscopy. It should be possible to develop a cluster of miniature spectroscopic tools that operates from mm-wave to X-rays detecting the molecular spectra in different regimes to accomplish a variety of science measurements between 2015 and 2025 (specifics developments include mW to tens of W, 3-5% band tunable THz sources for remote sensing, 10^9 - 10^{12} photons/s flux efficient X-ray tubes, sub 250 nm-UV lasers, and mW level mass ionizers).

Nanoelectrospray-integrated micro and nano-fluidic systems, or fully autonomous lab-on-a-chip systems, are expected to be ready for robotic and human explorations by 2030. It is expected that different developmental versions of these will be ready for qualification from 2016 to 2020, but automating it with suitable sample extraction, preparation, and waste rejection systems is expected to take additional years.

2.2.4.4. Key Capabilities

Key capabilities enabled by nanotechnology related developments in electronics, devices and sensors are in the Table below.

3. SUPPORTING TECHNOLOGIES

Successful development of nanotechnology and its implementation in NASA missions will require attention to and funding of several supporting technologies. While it was not possible to explicitly identify these technologies within each of the detailed roadmaps, they are critical to the accomplishment of technology entries within those roadmaps. For example, the development of high strength carbon fibers with densities less than 1 g/cc will require innovations in carbon nanotube synthesis to consistently produce carbon nanotubes of controlled diameter and length, improved fiber processing methods that give fibers with a high degree of nanotube alignment, new in situ characterization techniques to monitor nanotube alignment and the development of multiscale modeling and simulation techniques that can guide nanotube and fiber processing. Some of the challenges associated with these supporting technologies are discussed in this section.


The ability to produce nanoparticles and fibers with controlled size and morphology can have a broad impact on the development of technologies identified in each of the detailed roadmaps. Since Ijima's discovery of carbon nanotubes, there has been a highly intensive effort to develop controlled methods for carbon nanotube synthesis that can produce nanotubes of a given size (length and diameter) and chirality. Carbon nanotubes with long lengths and small diameters are desirable for optimized mechanical properties. Nano-

Grand Challenge - Hierarchical System Integration Issues (Nano to Micro to Meso) (2023-2028)

For any given Observatory-development, system-integration can be one of the most challenging aspects of the development. Facilitation of intra-instrument, intra-spacecraft, and instrument to spacecraft communication, power, data & telemetry collection, transfer, & storage, are both essential and highly complicated functions which must be enabled for any mission to perform effectively. The effective integration of nanotechnology products with applications requires resolving hierarchical system integration issues. It is expected that nanocomponents function as part of microsystems, or mesosystems that are in effect can be either stand-alone systems or sub-systems. High sensitivity sensors (ppb to ppm level), high-speed (hundreds of GHz) electronics, and measurement enabling nanocomponents for miniature instruments are bound to interface with larger (micro, meso, and higher) systems to accomplish desired operation. System integration issues at that level can pose significant challenges including: the design of devices and processes that are conducive for both nano and microstructure fabrication schemes (chemical, thermal, and mechanical issues), structural integration techniques that are mechanically and thermally robust, development of efficient interconnects, effect of nano-micro-meso interfaces, packaging, and signal interference at component level that can potentially degrade system performance. Overcoming these challenges systematically is critical, and it enables introduction of nanotechnology-based systems as identified in this roadmap into future NASA missions.



Capability/Sub-Capability	Mission or Roadmap Enabled	Current State of Practice	Time to Develop
Sensors and Actuators: Intelligent, Autonomous, Distributed and Embedded Sensing – (1) μ W chemical sensors for highly sensitive detection at ppb level, (2) embedded state sensors, (3) biosensors for molecular level detection, and for astronaut health diagnostics, (4) radiation sensors, (5) intelligent wired and wireless sensing network, (6) integrated chem-bio-rad sensing system	Ground support and launch pad safety, In-flight safety assurance, Human health and life support systems, IVHM, Earth science missions, Space suits, Entry decent landing probe/system	There are not many areas using sensors for real time monitoring. Only large scale electrochemical sensors are used in ISS and cabin air monitoring in shuttle. Platinum wire sensors for fuel tank level measurement	First use: 3-5 yrs Full potential: 5-20 yrs
Miniature Instruments: Cluster of miniature spectroscopic instruments and electronics including, (1) tunable THz tube sources for heterodyning, (2) high-flux, cold X-ray sources for mineralogy and elemental detection, (3) sub 250 nm UV lasers for molecular finger printing (Raman), and (4) mW-level, high resolution trace chemical detection (mass spectrometry), (5) microimaging, and (6) autonomous lab-on-a-chip systems, (7) broadband UV-IR detectors	Robotic Exploration Systems, Human Exploration Systems, air and space vehicles	Independent high-power (1 to ten W), large instruments (kgs) operating at elevated temperatures (>1200 C- need heaters)	First use: 5-10 yrs Full potential: 15-20 yrs
Fully capable smart, small satellites (100 g) with formation flying capability for science and inspection: Accomplished through high Isp (>1000 s) micropropulsion for 6 DOF flying, multifunctional structural material, low-power, high-density, rad-hard, wide-temperature swing tolerant electronics; MCMs; and highly miniaturized instruments and avionics.	Autonomous Systems, Distributed sensing, Large area aperture, and Robotic exploration	Limited capability kilogram-class spacecraft and aero vehicles with very limited capability	First use: 10-12 yrs
Extreme environment operations: See Lightweight Structures.			
Low power, rad hard reconfigurable computing: Novel component level technology (e.g. Graphene, carbon nanotubes, III-V nanowires, quantum dots, molecular electronics) and architectures (e.g., cross-bars) can potentially produce systems 100 – 1000X denser at constant power; small size (e.g. small target) for radiation tolerance; high density provides for embedded redundancy; time-dependent (selectable) nano-micro electronic interconnects for functional adaptation.	Human Exploration, Science, Aero Vehicles, Communications and Navigation	.13 μ CMOS, FPGAs, Si-Ge, GaN, radiation tolerant foundries; functional redundancy	10-15 yrs
On-Board Human Health Management: For long duration human space exploration beyond LEO, nano-systems such as a multi-stage lab-on-a-chip could be used for non-invasive physiological monitoring of individual biomolecules.	Human Health and Support Systems	Continuous medical contact with Earth, invasive physiological monitoring (e.g. blood samples)	Monitoring: 10-15 yrs Treatment: 20-25 yrs
Ultra-Sensitive and Selective Sensing: Sensors based on nano-structures such as quantum dots, nano-wires and DNA-like molecules can respond to a single photon and potentially a single molecule. They are well suited for longer wavelength sensors (e.g. visible-through-FIR) or distinct biological molecules or chemical agents.	Scientific Instruments and Sensors, Human Health and Support Systems	Standard semi-conductor and MEMS technology	Within 5 years Full potential: 10+ yrs
Modeling Fabrication Processes for Nano-to-Micro Interfaces: Efficient coupling of quantum, molecular and continuum mechanics for advanced electronic and sensor systems; critical for specialized systems development and integration. Hierarchically architected systems designs.	Scientific Instruments and Sensors; Multifunctional structures, instruments, sensors. Autonomous systems.	Laboratory demos. Lab scale demos of hierarchical structures similar to gecko feet.	8-10 years



tube chirality will dictate the electronic characters of the nanotubes, i.e., whether they have metallic conductivity, are semi-conductors or insulators. While some methods have been developed that produce mixtures of nanotubes of predominantly one size or chirality, no method has been developed to date that can produce nanotubes of a single size or chirality. As an alternative, significant research efforts have also been focused on the development of techniques to separate nanotubes by size or chirality. These approaches have met with some success. Recently, separation techniques developed by Nanointegris have been reported that are capable of producing 99% pure metallic and 99% pure semi-conducting carbon nanotubes.

Addition of nanoscale fillers into various matrices has been shown, in some cases, to lead to materials with significant improvements in mechanical, electrical and thermal properties. However, these property improvements often fall short of predicted values. New innovations in processing science are needed to fully translate the benefits of nanoscale particle addition on materials properties and enable the large scale production of nanocomposites with consistent quality. Characterization techniques are also required to monitor the processing of these materials in situ to enable better control of materials processing. Multifunctional materials developed through the addition of nanoscale additives will have to be qualified for use in NASA missions. This will require the development of new test techniques that can measure coupled properties and reduce the potentially high cost of qualifying these novel materials.

The development of efficient and robust multiscale modeling techniques is needed to guide materials synthesis and processing and to aid in understanding their mechanical, thermal and electrical behavior. Computational materials design is the use of theoretical methods to formulate chemical compositions, design nano and mesoscale morphologies and microstructures, and predict the macroscopic physical properties of materials resulting from this process. Examples of these theoretical methods include atomistic quantum mechanics, classical forcefield/potential based atomistic and coarse-grained molecular dynamics, discrete and continuum plasticity, and equivalent continuum and finite element modeling. The status of these methods fall all along the TRL scale, spanning from fundamental research (TRL 1-2) to highly developed methods that are routinely used and implemented in commercial software packages (TRL 8-9). Each method is designed

to work well for a particular size and time scale. To make meaningful contributions to new materials development, they must be linked together by concurrent or sequential multiscale methods to cover the full span of size and time scales that are operative in determining material properties and performance. Additionally, the development of appropriate experimental and processing methods is necessary to enable validation of the developed methodologies and to produce prototype materials.

The key challenges/gaps in computational nanomaterials are improving the constituent modeling approaches and linking them together to span multiple length and time scales. Advances are needed in quantifying linkages between nano-/micro-structures, defects and material properties in order to support the predictive power of computationally guided materials design. Improved microstructural evolution (processing models) for nanomaterials and hybrids of these materials with conventional metallic, polymeric and ceramic systems are necessary to advance the development of nanostructured materials processing. At the current level of technology maturation, computational nanomaterials design accelerates the process of creating new materials, reduces development costs, and results in materials that meet the property objectives. When fully developed, this technology will permit tailored design of materials and multi-material structures from the atomistic to macroscopic scales. This offers the possibility of significant weight reduction, dramatically improved mechanical properties, multifunctionality, and improved durability in extreme environments, all while reducing development times and costs. Many of the computational methods being developed to support design of materials also provide the basis for the analyses needed to analyze degradation of the materials throughout their operational lives and provide the foundation for the Digital Twin concept advocated by TA 11 and TA 12. All of the fundamental and practical technical barriers to achieving this vision are, in principle, surmountable. However, creating these tools will require a consistent and substantial level of effort and support, both internally and with collaborators in government, industry, and academia.

4. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

All of the other roadmaps can benefit from the fundamental capabilities derived from nanotechnology. The relationships are mostly “enhancing”

Technology Area	Lightweight Structure	Damage Tolerant	Coatings	Adhesives	Thermal	Sensors, Actuators	Electronics	Instrumentation	Nanopropellants	Propulsion Components	In-Space	Energy Generation	Energy Storage	Energy Distribution
Launch Prop.	X	X		X	X	X			X	X				
In-space	X	X		X	X	X			X		X			
Power					X		X					X	X	X
Robotics	X	X	X		X	X	X	X				X	X	X
Comm/Nav					X		X					X	X	
Human Health		X			X	X	X	X						
Surface Systems	X	X	X		X	X	X	X				X	X	X
Instruments						X	X	X				X	X	X
E,D,L	X	X			X									
Nano	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Modeling	X	X	X	X	X	X	X	X	X	X	X	X	X	x
Materials	X	X	X	X	X					X				
Ground & Launch			X			X	X			X		X	X	
Thermal			X	X	X									

and some of them are breakthrough due to the relative immaturity of nanoscale technology. As nanotechnology capabilities are proven, many will become “enabling.” A few specific areas stand out as having the broadest impact: high strength, lightweight materials; low power radiation/fault tolerant electronics; and high sensitivity/selectivity sensor systems. In particular, Scientific Instruments and Sensors (SIS) and Human Health and Support Systems (HHSS) consider nanotechnology to be enabling. Specific needs cited include: radiation hard electronics, lasers, miniaturized magnetometers, bio/chemical sensors, and far-infrared single photon counting sensors. HHSS has a strong dependency on nanotechnology for environment and human health monitoring; environmental protection; and process and control for critical systems (e.g. EVA, life support). A general conclusion across all capability areas is that nanotechnology is not identified with any one Mission Directorate or any unique set of missions. It should be considered an area for strategic investment by NASA, focused on critical needs, but recognized as having broad applications and benefits.

A matrix indicating the interdependencies of different grouped nanotechnologies is given below, with Xs indicating a potential interdependency.

5. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

In addition to meeting NASA needs, nanotechnology can also address National needs in clean energy, medicine and National security. Advanced structural nanomaterials and nanoengineered coatings can be used to develop lightweight, more damage tolerant turbine blades for wind energy that are less susceptible to ice accretion and insect fouling. Advanced aerogel insulation can be used to improve the energy efficiency of homes. Nanotube electrical wiring can have a significant impact on reducing resistivity losses in electrical power transmission lines. Advanced photovoltaics, batteries and fuel cells can also meet needs for clean energy storage and generation. Nanoelectronics, sensors and actuators, and miniature instruments have wide use in many applications to meet other National needs. For example, nanosensors possess high sensitivity, low power and small size that can fit in a cellphone for extended coverage of sensing network for homeland security applications in detecting toxics and chemical threats. Such a cellphone sensor can be used in a clinic or at home for medical diagnosis and health monitoring at the point of care as well. First responders for natural disasters and other accidents can also use it to determine the cause of the problem and make a decision at the point to have a solution for the problem. Nanosensors can form a wired and/or wireless network that can be used to monitor the safety of a building or a stadium as well as for battlefield chemical profiling.

ACRONYMS

ALICE	Nanoscale Aluminum-Ice Propellant
ARC	Ames Research Center
BN	Boron Nitride
BNNT	Boron Nitride Nanotubes
CFRP	Carbon Fiber Reinforced Polymer
CMOS	Complementary Metal Oxide Semiconductor
CNT	Carbon Nanotubes
CTE	Coefficient of Thermal Expansion
DNA	Deoxyribonucleic Acid
EVA	Extravehicular Activity
FET	Field Extraction Thrusters
FPGA	Field Programmable Gate Array
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HHSS	Human Health Support System
IR	Infrared
IKAROS	Interplanetary Kite-craft Accelerated by Radiation of the Sun
ISS	International Space Station
IVHM	Integrated Vehicle Health Management
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Flight Center
LaRC	Langley
LEO	Low Earth Orbit
MCM	Multichip Module
MEA	Membrane Electrode Assembly
MLI	Multilayer Insulation
MMOD	Micrometeoroid Object Damage
MSFC	Marshall Space Flight Center
MWNT	Multiwalled Carbon Nanotubes
NCSU	Nano Chem Sensor Unit
NNI	National Nanotechnology Initiative
PEM	Proton Exchange Membrane
PLSS	Personal Life Support System
POSS	Polyhedral Oligomeric Silsesquioxane
SIS	Science Instruments and Sensors
SWNT	Single-Walled Carbon Nanotubes
TPS	Thermal Protection System
UV	Ultraviolet

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