DIPLOMARBEIT

Nanotechnology Applications in Aerospace

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o.Univ.Prof. Dr.Dr.h.c.P.Herbert Osanna

Univ.Ass. Prof.h.c. Dipl.-Ing. Dr.techn.Ali Afjehi-Sadat

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Institut für Fertigungstechnik

eingereicht an der Technischen Universität Wien

Fakultät für Maschinenbau

von

Pelin Berik

Matrikelnummer 0325696

Czartoryskigasse,210-25,1170,Wien

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Abstract

The objective of this thesis is to explore and discuss the potential of nanotechnology applications in aerospace.

Space has been always the unknown and the unreachable for humans and they tried to find the ways to explore it. Space played an important role in the advance of technologies. We created many new technologies to reach space, to find the unknown; it was an accelerator of the technology. Nanotechnology is one of the most important technologies of the century with its new materials, techniques and wide application areas. Nanotechnology allowed incredible advances in space technology. With nanotechnology considerable reduction of mass, volume, power consumption and cost can be achieved in space applications. Spacecrafts are being launched that are composed of light weight high strength nanomaterials. Carbon nanotubes provide the highest strength-to-weight ratio of any material ever seen. Nanotechnology supplies new concepts for protection shields against the triple threats of aero-heating during atmospheric entry.

Another application of nanotechnology is nanorobots. Nanorobots can carry out projects in hostile environments. The solar system can be explored by nanorobots with their high autonomy and improved capabilities. Nanotechnology also revolutionizes the field of satellite design, sensors and actuators.

The development of nanotechnology makes the exploration and future settlement in space possible. Nanotechnology improves the performance and the reliability of aerospace hardware and lowers manufacturing costs.

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1. Space

1.1 Space and Aerospace

Space is the endless empty part of the universe; it constitutes the universe with other scattered cosmic objects and materials. Aerospace comprises Earth's atmosphere and the outer space and is a more specific word than space. Space can describe any of the empty three dimensional parts in the universe, but aerospace can be only used with our planet. A travel in aerospace is a travel in the air and space.

1.2 Solar System

The origin of our Solar System is discussed in many astronomy texts. Evidences support that our Solar System is a result of star formation. The Solar System formed from a cold, rotating clump inside a Giant Molecular Clouds. The initial cloud or nebula consisted of roughly 90 % hydrogen, 9 % helium with a small proportion of more dense elements and carbon particles. When the cloud begins to shrink, it spins faster in order to conserve angular momentum and the centrifugal force causes it to flatten into a disk-like shape. As a result the centre of the solar nebula forms the Sun and the planets form in the disk of the solar nebula. This flattening idea gives an explanation about the regularities of the planets. Orbits are in the same sense and co-planer; the rotations of planets are in the same sense as the orbital motions. The moon orbits are in the same sense as the orbits of planets [Chaisson and McMillan, 1996].

1.3 The Beginning of Exploration of Space

Human being believed always it would be possible to explore the space. Jules Verne's first science fiction work was “From the Earth to the Moon” in 1865. Jules Verne was an inspiration for Tsiolkovsky to write his stories about inter-planetary travel. Konstantin E. Tsiolkovsky, Robert H. Goddard and Hermann Oberth were the pioneers of space. In 1903 Russian space pioneer Konstantin Tsiolkovsky published his book about the basic scientific principles for space travel. "The Exploration of Cosmic Space by Means of Reaction Devices" was the first academic study on rocketry. German Scientist Hermann Oberth's work - The Rocket into Planetary Space- gave the first mathematical and physical design concepts to design a vehicle which takes man to the earth orbit. Oberth proposed the construction of observation stations in orbit with his work. Wernher von Braun who was a student of Oberth proved that it was possible to build a machine for space travel. In 1942 the first successful launch of the V2 rocket was accomplished [Freeman, 2000].

In 1963 NASA's (The National Aeronautics and Space Administration) Manned Space Flight began for the travel to the moon with the space programmes: The Merkury, Gemini and Apollo. The aim was to show that man could safely reach to the Earth orbit, travel to the moon and then return. In 1965 Saturn V rocker achieved the first unmanned test flight to the moon. Apollo 11 was the first manned mission to land on the Moon. In 1969 Neil Armstrong, Edwin Aldrin, and Mike Collins landed on the Moon and returned to the earth.

1.4 Space Stations

Skylab was the first space station of the USA and was launched into orbit in 1974 (Figure 1.1). This space station was divided into two floors to conduct various activities. The first floor had both the function of a house and experiment, exercise facilities for astronauts to adapt themselves to weightlessness.

Figure 1.1: America's first space station, Skylab-NASA

The second floor was like storage for supply of water, consumables, and had an astronaut-maneuvering unit for the test studies of NASA's future Space Shuttle. Experiments have been also performed.

The Airlock Module attached to the orbital workshop allowed crew to exit the space station and also performed emergency Extravehicular Activities (EVAs). The crew traveled to open space through an EVA hatch. The nitrogen and oxygen storage tanks were mounted on the truss frame of the Airlock Module. They were required as life support system of the space station. The Airlock Module contained also communication, data handling and recording, the electric power control and distribution systems.

The Multiple Docking Adapter (MDA) was attached to the Airlock Module. It provided the portals allowing Command-Service Module and the entrance of the crew. The required experiments were mounted in the MDA; materials processing activity, earth resources experiment package, and the control the display console for Apollo Telescope Mount. Therefore Skylab could provide views of earth. Skylab contained human occupants during 171 days and completed its mission. It has proved that man could live and work in space for months. Hundreds of measurements are made during these months.

The late 1970s and early 1980s the United States had no manned flights into space. In February 1986 the first module, the base block of the Mir station was launched into orbit by Soviet Union. On January 28, 1986, the Space Shuttle Challenger had exploded short after its launch; all seven crew members were died [Freeman, 2000].

The Shuttle-Mir program started a new phase of manned space exploration (Figure 1.2). Russia's Mir Space Station was the first modular station and largest spacecraft that ever existed in space until the construction of international space centre.

Figure 1.2: Mir on 24 September 1996-NASA

Mir was constructed of different modules that were pieced together. The first module was the main module of the station. It provided docking ports for the other modules to attach to. There were six docking ports of the Mir module. Other various modules could also be attached later and moved around to different configurations.

The Soyuz-TM spacecraft was used to transport crews and cargo to and from the Mir Space Station. The Soyuz could dock on the axial docking port on the transfer compartment. The Progress-M spacecraft was a cargo vehicle to send science equipment and data. It has been also used to conduct experiments. When sent back to Earth, it could remove waste materials from the Space Station [Portree, 1995]. The station existed until March, 2001, and then it was de-orbited and broke apart during atmospheric re-entry and fell into the South Pacific Ocean.

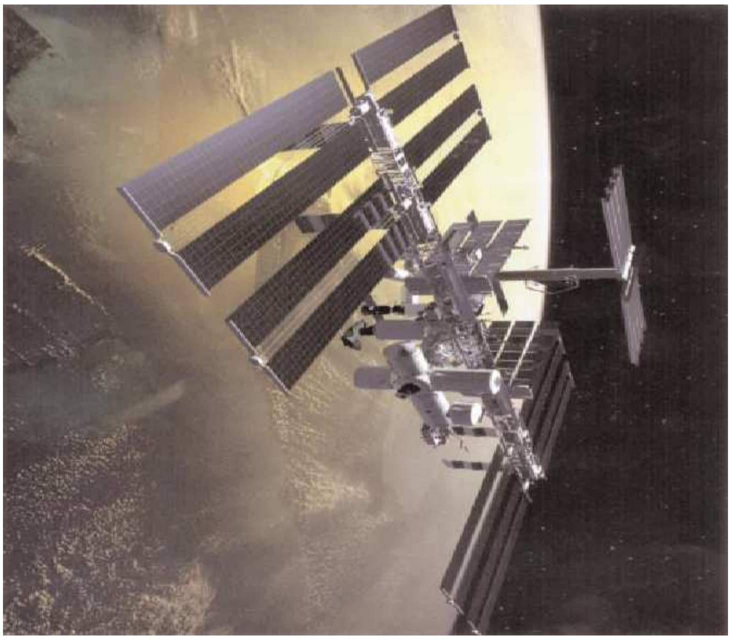


Figure 1.3: International Space Centre- NASA

The International Space Station (ISS) is an orbital laboratory for long-term research. Chemistry, physics, ecology, and medicine experiments are conducted using the most modern tools [NASA LG-1999-06-455-HQ] (Figure 1.3). ISS is the largest and most complex international scientific project in history. It has a mass of about 1,040,000 pounds and measures 356 feet across and 290 feet long, in an orbit with an altitude of 250 statute miles (1 statute mile is about 1,609 m), with an inclination of 51.6°. This permanently human occupied platform is a step for the future space exploration.

On-orbit assembly began on November 20, 1998, with the launch of the first ISS component, Zarya (Sunrise) Control Module on a Russian Proton rocket. Zarya Control Module provides attitude control and propulsion during the early assembly operations, solar power and ports for the addition of other modules. The Space Shuttle has carried the U.S.-built Unity connecting module on December 4, 1998. The Zvezda (Star) Service Module provides initial living areas and life support systems. Permanent habitation of the ISS began in 2000 with the launch of Expedition 1 aboard a Russian Soyuz capsule [NASA LG-1999-09-522-HQ].

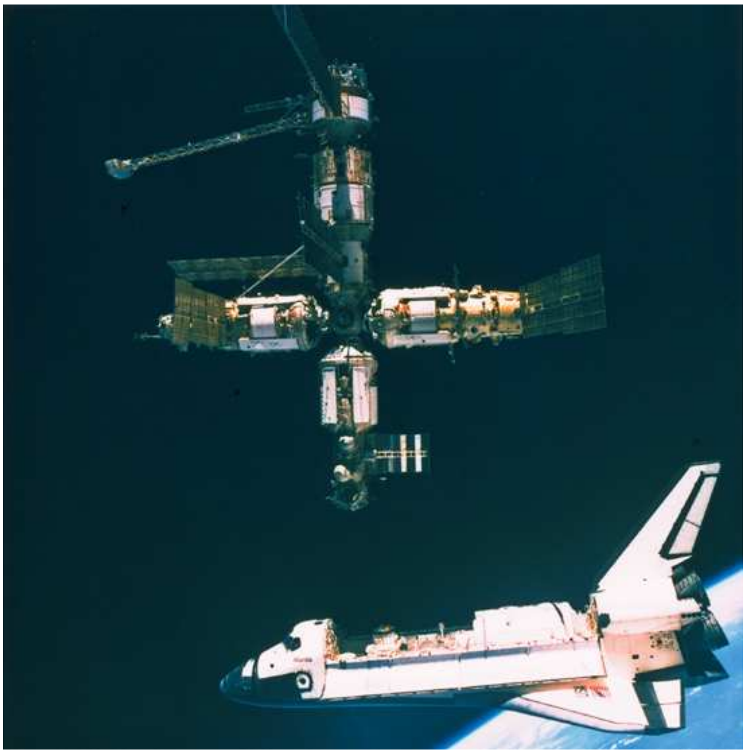


Figure 1.4: Shuttle-ISS Docking Module- NASA

1.5 The role of International Space Station for Nanotechnology

One of the effects of space environment is microgravity. International space center is an important laboratory for the execution of microgravity experiments. Nanotechnology related microgravity experiments deal with gas phase synthesis of nanopowders and particles, ferrofluids, plasma crystals, aggregation of nanoparticles, self assembly, atomic force microscopy, scanning tunneling microscopy.

The SPM (Scanning Probe Microscope) equipments are small and they can work without vacuum or high voltage supply. Because of that, SPMs are suitable for applications in space. They can be used on the International Space Station (ISS), or on planetary missions. An ISS microscope combination of atomic force microscope and a scanning tunneling microscope can be used for examination of materials and surfaces experiments, in situ studies and crystal growth on board [Drobek, Reiter, Heckl; 2004].Self assembly is important for the bottom up building of nanotechnology. With the aid of on the ISS executed experiments, we can determine if self assembly is dependent on gravity. Microgravity allows more detailed observation of agglomeration process. The formation of nanoparticles in flames is another focus point for microgravity research.

2. Nanotechnology

Nanotechnology is the creation and manipulation of materials, processes and devices at the atomic scale. Nanometer indicates one billionth of a meter (1 nm=10^{-9} m). Nanotechnology can be regarded as molecular engineering or molecular manufacturing. By organizing individual atoms and molecules into particular configurations, it is possible to create useful and functional materials with desired complexity and size. Precise control of matter at atomic level is increasing in the laboratory nowadays. Nanotechnology is more specific than chemistry. It observes atoms and molecules visually and manipulates them at the nanoscale level.

Taniguchi introduced the term nanotechnology in 1974 to describe precision manufacture of parts with finishes and tolerances in the range of 0.1 nm to 100 nm and the metrology respectively [Taniguchi, 1974]. Nanometrology is the science of measurement of geometrical features of size, shape and roughness of nanoscale structures and systems. Measuring equipment is an important quality requirement at the higher demands of micro and nanotechnology [Osanna, Durakbasa; 1999]. Professor David Whitehouse is an internationally acknowledged expert in nanometrology. In 1981 Drexler indicated that materials can be constructed with bottom up approach. Nanotechnology is the atom manipulation at the molecular level. It enables us to build new molecular systems with atom by atom precision [Drexler, 1981]. Nanometer accuracy requires enhanced exactness of measurement [Whitehouse, 1990]. The most important aim of nanotechnology is to define concrete accuracy for processed products at atomic scale [Taniguchi, 1996].

One of the new substances that have been created by scientists are nanotubes, a form of tubular fibers. They can be joined and crystallized. Although nanotubes are thin, they are 100 times stronger than steel. Nanotubes can bring new solutions and new ways for the exploration of space, like the concept of a space elevator. Space elevator is a device for putting spacecraft into orbit. The structure of the space elevator (chapter 4) could be very heavy and thick with the use of steel, but it is now more reachable by nanotechnology. For the construction of solar sails which is a new type of future transportation light weight materials are needed too.

Swarms, a type of nanomachines, can be also produced by the manipulation of atoms and they can be used to carry out dangerous jobs in space.

Nanotechnology will allow scientists to produce new materials which are strong and flexible to manufacture lightweight space vehicles.

2.1 Tools to "See" and Control Atoms

2.1.1 Electron Microscopes

The examination of very small objects is achieved by the use of a beam of high energy electrons. Electron microscopes give information about topography, crystallography and morphology. Topography gives the information of surface features of materials like appearance, hardness, texture. Crystallography is related with the arrangement of materials. Morphology defines the size and the shape of particles which make up the object.

The transmission electron microscope (TEM) was the first stage of electron microscopes and invented in early 1930s.In TEM a beam of electrons is used instead of light to see the material. The procedure used in TEM is as follows: By an electron source a stream of electrons is formed and accelerated toward the specimen with a positive electrical potential; using metal apertures and magnetic lenses the stream is confined into a thin monochromatic beam; using magnetic lenses the beam is focused onto the sample. Inside the irradiated sample interactions occur and affect the electron beam. Effects are detected and then transformed into images [Wilson, 2002].

2.1.2 Scanning Electron Microscope (SEM)

The scanning electron microscopes were invented in 1942. Scanning Electron Microscopy (SEM) uses a focused electron beam to scan the area of sample. SEM can create images more clearly than TEM and three dimensionally. Transmission electron microscopes create images with higher magnification. However, the range of magnification of SEM is wider. The range is from 10 to 100 000 times of their normal size. A beam of electrons is emitted by an electron gun. A condenser lens refines the beam of electrons into a stream and focuses it onto the sample. When the beam hit the sample, several interactions cause a radiation. This deflected radiation is sensed by a detector and converted to an image [Wilson, 2002].

2.1.3 Scanning Tunneling Microscopy

The starting point of SPM was the invention of the scanning tunneling microscope (STM) by G. Binnig and H. Rohrer in 1982 [Binnig, Rohrer; 1982]. Scanning tunneling microscopy is also used to manipulate molecules. The STM scans the surface by a metal needle, records the height of the tip or the topography of the surface (Figure: 2.1). It maintains the tip within a few atomic diameters distance to the surface. This is achieved by a current between the tip and surface. The magnitude of the current is sensitive to the distance between the tip and the surface [Osanna, Afjehi-Sadat, Durakbasa; 2004b]. The tunneling of electrons through vacuum from the tip of the STM to the sample is the procedure for the function of this microscopy. STM is very accurate but can only be used with conducting materials.

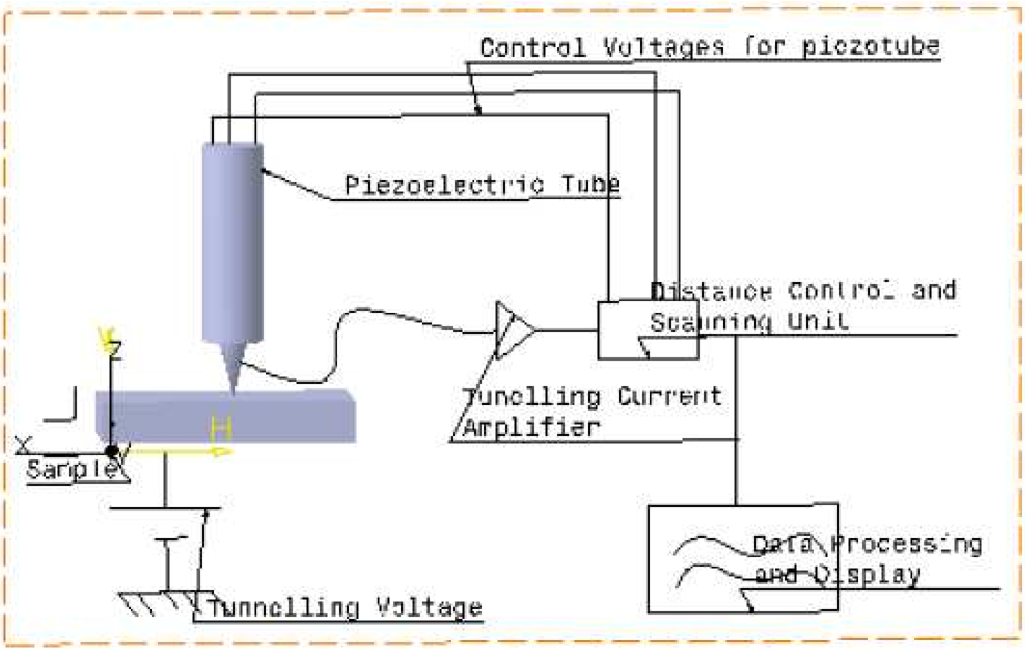


Figure 2.1: Scanning Tunneling Microscope; re-illustrated by Pelin Berik.

2.1.4 Atomic Force Microscopy (AFM)

Atomic Force Microscopy is a high-resolution imaging technique that can resolve features as small as an atomic lattice. AFM observes and manipulates molecular and atomic level features. The images that are created by AFM are a combination of the sample surface and the probe [Osanna, 2001].

AFM has enormous potential and application because it can be used for imaging any conducting or non-conducting surface. AFM applications have exploded since it was invented in 1986 and now encompass many fields of nanotechnology. We are able to view and understand events occurring at the molecular level with AFM.

AFM brings a cantilever tip in contact with the surface to be imaged (Figure 2.2). An ionic repulsive force from the surface applied to the tip bends the cantilever upwards. The amount of bending, measured by a laser beam reflected on to a split photo detector, can be used to calculate the force. By keeping the force constant while scanning the tip across the surface, the vertical movement of the tip follows the surface profile and is recorded as the surface topography by the AFM.

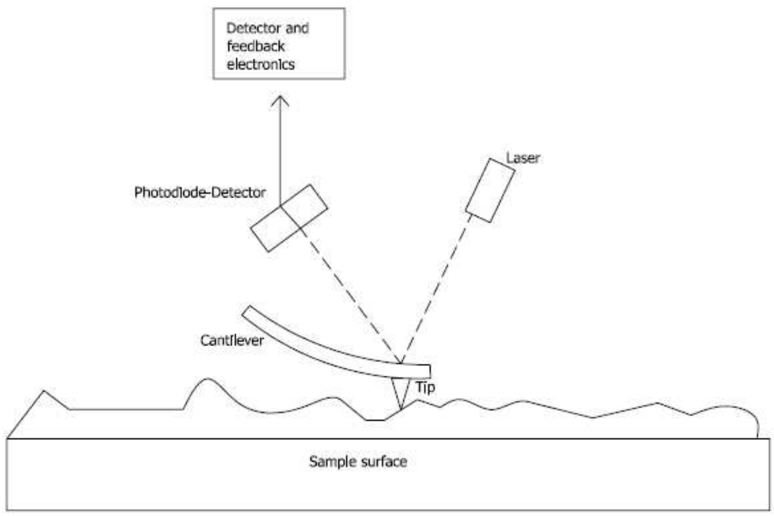


Figure 2.2: Atomic Force Microscopy; re-illustrated by Pelin Berik.

In AFM Van der Walls forces are usually sensed from a surface. In this way measurement of nonconductive surfaces as well as operation in air and liquid is possible. An AFM can be used to measure chemical forces between the tip and a surface, when chemically active molecule is placed on the tip.

A sharper tip is necessary to achieve higher resolution, and measure the interaction of individual molecules with a surface. [Dai, 1996] attached carbon nanotubes to SPM tips to achieve atomic precision. [Wong, 1998] used open ended carbon nanotubes, covalently functionalized with several different molecules, to image a chemically varied surface. A lateral chemical resolution of approximately 3 nm is achieved. This value is better than the obtained value with the use of Si and Si3N4 (15 nm) or multi-walled-carbon-nanotube tips (8 nm).

When the sample with different functional groups on the tip is scanned, totally different images and the differences can be obtained by the basis of chemical affinity between the tip and the surface. Closed and open carbon nanotubes may be functionalized in many ways therefore modified nanotube probes can perform high precisions and overcome reaction barriers.

2.1.5 Scanning Probe Microscopy (SPM)

Scanning probe microscopy contains several new developed microscopy technologies and a collective term. The most popular SPM technologies are Atomic Force Microscopy and Scanning Tunneling Microscopy and they have a similar operation. Scanning probe microscopes position precisely atoms and molecules on a surface (Figure 2.3). Control of atoms and molecules can be accomplished electronically, mechanically with chemically active tips. The interaction of a microscopic probe with the surface of a sample measures characteristics of the sample at localized points. A sharp silicon tip is used as the probe is typically, but can also be other materials, like single walled carbon nanotubes [Dai, 1996].An image is produced by scanning the sample with a probe in a two-dimensional pattern. The motion of the sample is usually controlled by piezoelectric materials, sometimes to sub-atomic accuracy. The interaction is quantified by measuring the deflection of the cantilever, often with a laser. Extreme accuracy is obtained with a feedback loop between controller and the deflection measurement system. Lateral resolutions up to 10 nm can be obtained with scanning tunnelling and scanning probe microscopes [Osanna, Afjehi-Sadat, Durakbasa; 2004a].

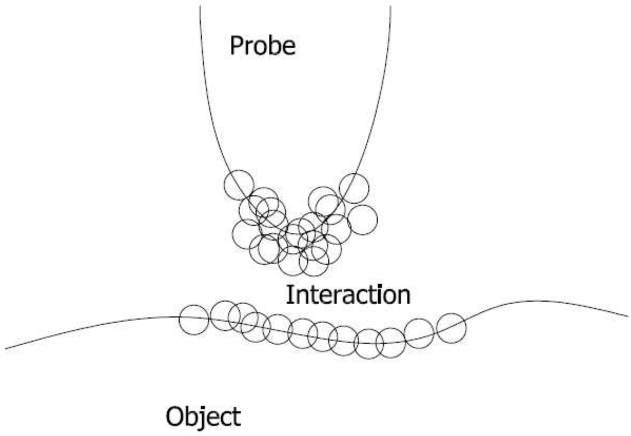


Figure 2.3: Probe Microscope Tip; re-illustrated by Pelin Berik.

2.2 Preparation of Nanomaterials

In principal six methods exist to produce nanomaterials:

- plasma arcing,
- chemical vapor deposition,
- electrodeposition,
- sol-gel synthesis,
- ball milling and
- the use of natural nanoparticles.

Plasma arcing and chemical vapor decomposition is based on the separation of molecules and atoms by vaporization. Then these vaporized molecules and atoms are allowed in a controlled way to deposit to form nanoparticles. Similarly in electrodeposition there is a deposition process. Sol-gel synthesis requires before deposition some ordering of materials. By ball milling nanocrystalline structures are produces from macrocrystalline structures with retain of originality of the material. New materials can be formed from nanoparticles.This involves the breaking of original crystallite bonds.

2.2.1 Plasma Arcing

A potential difference is applied across the two electrodes till the gas ionizes and conducts electricity and this forms the plasma. The electrodes can be volatile in a vacuum or in an inert gas. Electrodes or other materials can be volatilized and ionized by using heat. Plasma arcing is especially important in the manufacturing of carbon nanotubes. Two electrodes form a plasma arcing device and between these electrodes an arc passes. By the potential difference as electrons are taken away, the first electrode, anode, vaporizes. In the production of carbon nanotubes carbon electrodes are used. After the formation of carbon cations, they pass to the other electrode and collect electrons. At the end for the formation of nanotubes they are deposited.

Electrodes must conduct electricity, can be made of a mixture of conducting and non-conducting materials. This method is similar to the chemical vapor deposition method but here some materials are ionized. It can produce deposits on surface with the condition that at least one dimension of the bulk particle of the surface deposit is nanometer scale.

2.2.2 Chemical Vapor Deposition

In this method nanoparticulate material is deposited from the gas phase. Firstly by heating, gas is formed from the material and then under a vacuum it is deposited on a surface as a solid. New product differs from the deposited original material. When vapors of carbons or oxygen exist with the metal, nanpowders of oxides and carbides of metals are formed by this process.

Pure metal powders can be produced by using microwaves which are tuned to metal excitation frequencies to melt and vaporize the reactants in order to produce plasma up to 1500 C°. The formation of nanoparticles is achieved with the entry of plasma to the reaction column. The reaction column is cooled by water. Particle grain size, their distribution is affected by metal concentration in the gas phase, flow rate of metal vapor and temperature.

The growth of the surface is achieved by chemical vapor deposition. The object to be coated stays in the chemical vapor. Firstly deposited atoms or molecules may react with the surface. Dip pen nanolithography is also used to write on the surface and the molecules can be controlled and placed precisely. But chemical vapor deposition can build nanostructures rapidly by self assembly. In self assembly molecules and atoms organize and line up themselves naturally to reach the minimum energy.

2.2.3 Sol-Gel

Sol-gel formation is a self assembly process involving the evolution of networks in the formation of nanomaterials. This evolution realized through the formation of a colloidal suspension named sol and gelation of sol to form a network in a continuous liquid phase named gel. These colloidals consist of ions of a metal, or other elements containing several reactive materials. Because of their easy reactivity with water, metal alkoxides and alkoxysilanes (tetramethoxysilane and tetraethoxysilane which form silica gels) are widely used. The stages related to the sol-gel formation are: hydrolysis, condensation and polymerization for the formation of particles, growth of particles and the agglomeration of particles and then the formation of a gel.

2.2.4 Electrodeposition

Electrodeposition is a deposition method for the production of electroplated materials. The weight of the material transferred can be controlled by the control of transferred electrons. The aim of electrodeposition in nanotechnology is the placement of layers on a surface precisely like the production of nanostructured films of platinum from liquid crystalline mixtures. Nanostructures films can be also obtained from Pd, Ni, Au, organic polymers like polyaniline, oxides, and semiconductors. This method can also be applied to fill holes to make dispersed nanomaterials. These holes placed in membranes with the bombardment of a polymer sheet by energetic heavy ions. Nanocomposites are produced by filling of nanosized holes in polymer membranes with various metals. Such materials can be used for heat and radiation protective shields.

2.2.5 Ball Milling

Early nanomaterials were made by a simple method called ball milling. In ball milling small balls are rotated inside a drum and then they drop with gravity force on to a solid enclosed in the drum. The structure is broken down into nanocrystallites by this method and it can be implemented very commercially. Carbon nanotubes, other types of nanotubes like boron nitride nanotubes, and metal oxides can be produced by ball milling [Wilson, 2002].

2.3 Nanomaterials for Space Structures

Nanomaterials are lightweight, flexible materials with high fatigue strength and in the range of 1 to 100 nm. Nanostructures are mostly composed of the column IV elements Ge or Si, column III-V semiconducting compounds like GaAs or group II-VI semiconducting materials like CdS. Zinc oxide, cerium oxide, carbon black and fumed silica are typical nanomaterials. The majority of atoms are situated on the surface of particles in nanomaterials. Materials with big surface areas have improved mechanical, chemical, magnetic and optical properties, and this makes them available in aerospace applications. For example, materials produced from metal and oxides of silicon and germanium shows superplastic behavior. Before failure they can experience elongations from 100 to 1000 %. The nanosized particles can move relative to each other and that makes possible increased flexibility [Wilson, 2002; Poole, Owens 2003]. Space exploration missions in harsh conditions require high strength materials for the production of spacecrafts. Reduction in the grain size of the material causes an increase in the fatigue strength of the material. Because of that nanomaterials have a 200-300 % increased fatigue life with their reduced grain size.

Numerous studies report that space environment damages to man-made bodies in orbits are due to radiation (atomic oxygen, vacuum ultraviolet, proton, electron and particle) and thermal cycling. They contribute to material degradation, and reduce the lifetime of the orbiting body. Advanced materials like nanomaterials will be used in future space vehicle constructions.

2.3.1 Nanopowders

The nanopowders create more thrust in solid-propellant rockets, because of their increased surface area. Polymer coatings and addition of a stabilizer prevent the agglomeration of the particles. Aluminium or boron oxide nanopowders coated with thin polymer films with thickness between 20 and 300 nm prevents agglomeration. Therefore they can be used as solid propellants in rocket engines. Through addition of nanopowders to hydrocarbon fuels an increased power density can be obtained for liquid propellant rockets. Nanopowders ethanol/LOX (liquid oxygen) can also be used for bi-propellant systems [Mordosky, 2001].

2.3.2 Nanoparticle reinforced polymers

In space applications polymers are desirable materials. However, it has been proved over the last two decades that polymers used in the construction of space vehicles go through considerable degradation and result in reduced spacecraft lifetimes. Modifications of these materials can solve many problems in the space industry and offer new capabilities for future space systems. Electromagnetic radiation, space-borne particles in earth orbit, and oxygen attack can disturb the stability of polymers. Another concern for polymers is its inability to withstand the thermal cycling (–180 °C to 500 °C) occurred in orbit. Nanocomposite polymers can have a significant role for space systems in low-thermal expansion, space-resistant membranes and coatings applications.

The mechanical properties of polymers can be improved by dispersion of nanoparticles in polymer matrices. In this procedure as nanoparticle especially silicates (montmorillonite class), Polyhedral Oligomeric Silsesquioxanes (Polyhedral Oligomeric Silsesquioxane) and carbon nanotubes can be taken into consideration. As polymer matrices for example epoxide, nylon, polyphenole or polyimide can be used. POSS materials are considered as replacements for the metal bodies of missiles and satellite launch rockets. They are appropriate for these applications because they offer effective protection from collisions with space debris and the extreme thermal environments of deep space and atmospheric re-entry. POSS nanostructures are extremely resistant to atomic oxygen. The silsesquioxane (RSiO1.5) moiety apparently reacts with the oxygen to form a silica (SiO2) protective layer. This reaction was observed in POSS-Kapton, POSS-PDMS and POSS-Polyurethane nanocomposites. X-ray photoelectron spectroscopy (XPS) shows the degradation pathways for polyimides under attack by atomic oxygen. POSS Kapton has a 9x improvement in ablation resistance even under extremely high energy atomic oxygen attack; for this reason this material has great potential for a substitute for space resistant polymers [Hoflund, Gonzales, Phillips; 2001]. Nanoparticle reinforced polymers have application potentials for various components in space, among other things as housings of solid-propellant rockets, as heat protection material in rocket nozzles, electrical isolations or fire protection applications.

2.3.3 Carbon Nanotubes

Carbon nanotubes have been discovered in 1991 by Iijima [Iijima, 1991]. They can be seen as a sheet of graphite rolled into a tube with bonds at the end of the tube which close the tube. With their electronic, mechanical, optical and chemical characteristics they are available for future space applications.

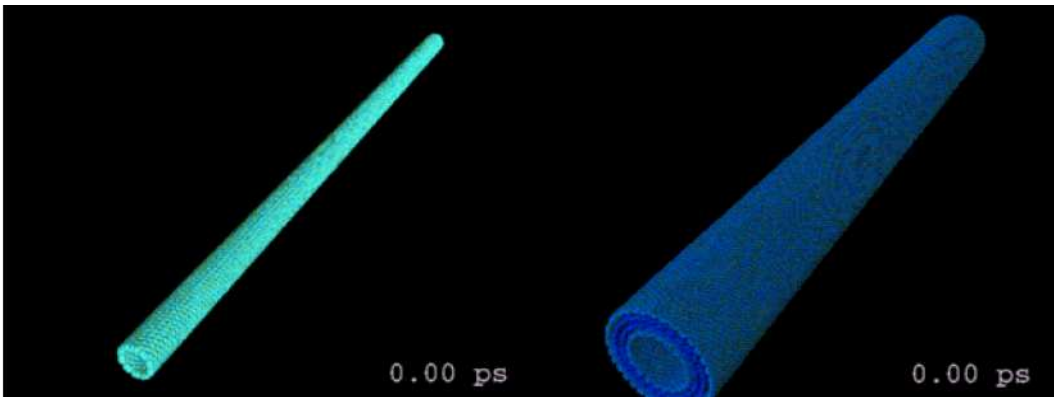


Figure 2.4: Single-and multi-walled nanotubes- image gallery, Nanotechnology Team, NASA.

A nanotube can be only one tube of graphite, single-walled nanotube (SWNT); or consist of several of concentric tubes, multi-walled nanotubes (MWNTs), shown in the Figure 2.4, 2.5. The graphitic sheet can be rolled in different ways; therefore there are different types of SWNTs [Wilson, 2002]. A single-walled nanotube can also called as nanowire because of its one dimensional form with a diameter of 2 nm and a length of 100 µm [Poole, Owens 2003]. Because of their special properties, CNTs have several application areas in space like the production of space structures, thermal control devices, sensor technology, and electronics. If we achieve to manufacture economically priced CNT in the future, we can not only produce improved conventional spacecraft, but also manage space applications sounding very unordinary now, for example a space elevator.

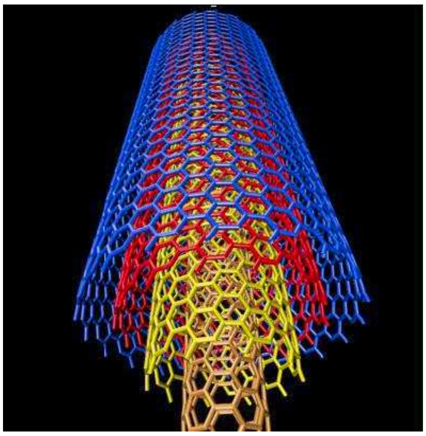


Figure 2.5: Multi-wall Carbon Nanotubes- Courtesy of A. Rochefort, Nano-CERCA, University of Montreal, Canada.

Carbon nanotubes can be produced in various ways like plasma arcing, laser ablation, chemical vapor deposition, ball milling and flame synthesis. Purification techniques of the tubes are oxidation, acid treatment, annealing, sonication, filtering and fictionalization.

Plasma arcing involves the evaporation of one electrode as cations and then deposition of them at the other electrode.

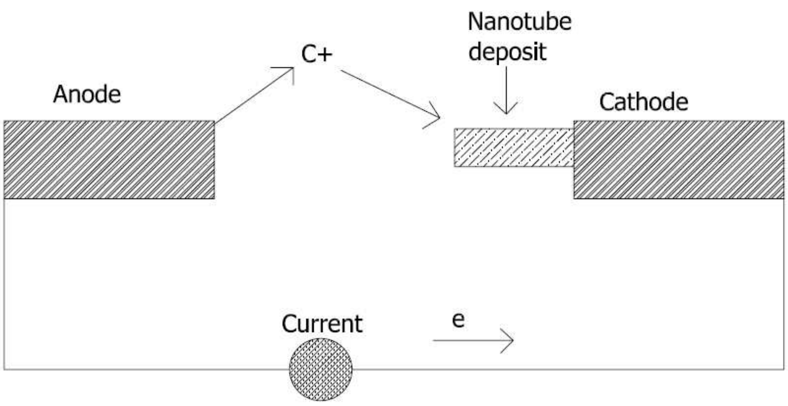


Figure 2.6: Plasma arcing- Carbon is evaporated from the anode and then deposited on the cathode- illustrated by Pelin Berik.

Carbon nanotubes produced by plasma arching from pure graphite electrodes are multiwalled, but when the anodes are doped with cobalt or other materials are given into the electrodes, they are single-walled. [Wilson, 2002]

In *Laser Ablation,* synthesis of carbon nanotubes by laser vaporization was achieved by Smalley's group at Rice University in 1995. SWNTs are produced by a dual-pulsed laser vaporization of graphite rods with an equal mixture of Co and Ni powder. The use of two laser pulses minimizes the amount of deposited carbon. With the second laser pulse larger particles ablating from the first laser can be broken up into smaller groups. The produced material was 10-20 nm in diameter and up to 100 μm in length. The nanotube diameter can be varied by varying the growth temperature, the catalyst composition and other process parameters.

For obtaining high quality carbon nanotubes laser vaporization and arc-discharge are the main methods, but these methods have some deficits like the unclear scaling in the production and unwanted forms of carbon nanotubes. For building nanotube devices the nanotubes are difficult to control and to purify with these methods. By catalytic deposition (*Chemical Vapor Deposition)* of acetylene over Co and Fe catalysts supported on silica or zeolite at 700 °C, large amounts of carbon nanotubes can be produced. The formation of SWNT are possible from ethylene with Fe, Co, Ni supported catalysts.

In *Ball Milling* graphite powder with 99.8% purity is loaded into a stainless steel container along with four hardened steel balls, then the container is purged and 300 kPa argon gas is given. The milling takes up to 150 hours at room temperature. After milling procedure, the powder is annealed at 1400 °C under nitrogen or argon for six hours. A nanotube nucleus is formed by ball milling and the growth is achieved by the annealing process. Multi-walled nanotubes are formed by this method but single-walled nanotubes are difficult to produce [Ding, Lu, Yan, Wilson; 2001].

In *Flame Analysis,* the flame supplies the efficient energy and hydrocarbon reactant. Combustion of hydrocarbon gives the required elevated temperature and the remaining fuel serve as the hydrocarbon reagent.

Special properties of carbon nanotubes

The chemical, electrical, optical and mechanical properties of carbon nanotubes are mainly affected by their one dimensional structure.

Chemical Reactivity: The chemical reactivity of carbon nanotube is higher than a graphene sheet. The reason of higher is the enhancement by the curvature of the CNT surface and pi-orbital mismatch caused by an increased curvature.

Electrical conductivity: Diameters of carbon nanotubes determine that they are metallic or semi-conducting. This property depends on their chirality. It presents the way the tubes are rolled. Different molecular structure causes a different band structure and thus a different band gap. A (n,m) nanotube is metallic if: n=m or (n-m) = 3j, where j is an integer and n and m are defining the rolling art of the nanotube. The conduction resistance is independent of the nanotube length but dependent of quantum mechanical aspects [Tans, 1997].

Optical activity: if the nanotubes become larger, the optical activity of chiral nanotubes disappears. It can be assumed that other physical properties are also influenced by these parameters. Use of the optical activity property gives CNTs an important role in the use of optical devices [Damnjanovic, 1999].

Mechanical strength: They have a very large Young modulus in their axial direction. They are very flexible because of the great length.

2.3.4 Metal-Matrix-Composites

The thermomechanical properties of Metal-Matrix-Composites can be improved by reinforcement of them with ceramic fibers, especially silicon carbide, aluminum oxide or aluminum nitride. These metal matrix composites like SiC in aluminum alloys or TiN in Ti/Al alloys, have a high potential for aerospace applications and are regarded the best the replacement of magnesium and aluminum in spacecrafts because of their high heat resistance, firmness, thermal conductivity, controllable thermal expansion and low density. Through reinforcement the strength of MMC can be increased up to 25 % and beside that, superplasticity and a better resistance against material fatigue can be achieved.

2.3.5 Nanostructured ceramics and ceramic nanopowders

The improvement of thermomechanical properties, fracture toughness and superplasticity of ceramics which are considerably brittle can be achieved with the production of nanostructured grain sizes. By applying nanopowders the consolidation time and the sintering temperatures of ceramics can be reduced. Ceramic nanopowders can be manufactured with adjustable powder grain size and both gas and liquid phase processes are used for the production of them. For the production of oxidic powders like Al2O3, SiO2 sol-gel procedures and for non-oxidic powders like Si3N4, SiC, TiCN gas phase processes are possible.

Nanostructured ceramic composites will have an important contribution in space applications as thermal and oxidative protection for fiber-reinforced construction materials like coating of carbon fiber materials with boron nitride. They have also application areas in optoelectronics and sensor technology.

2.3.6 Nanomaterials for Thermal Protection

In space applications, because of unordinary environments, the right thermal protection system has a significant importance. Higher flexibility and security, reduction in cost for spacecraft can be achieved with an improved thermal protection system. Ceramics for protective layers or fiber composites are especially in the usage.

For re-usable high temperature components like nozzles, combustion chambers of rocket engines or heatshields of reentry space systems ceramic fiber composites are used. For the development of thermal protection systems, nanopowder (SiC, Al2O3), nanostructured ceramic fibers, fiber coatings with nanoscale texture, ceramic matrix from silicon-organic oligo- and polymer precursors for complex structures and substrate foils from oxide ceramics for reflector layers like internal multi-screen insulation have importance [Paschen, 2004].

Nanostructured diamond-like carbon layers have four times higher thermal conductivity than copper. Therefore thermal control systems of nanosatellites can be improved by diamond-like carbon layers. They also provide corrosion protection against atomic oxygen [Rossoni, 1999].

2.3.7 Nanomaterials for Space Sensors

Gas sensors

In space applications, gas sensors are used for the detection of hydrogen leakages in rocket engines, for the measurement of the oxygen content in upper atmosphere layers or for the monitoring of the air quality in manned space systems. There are three types of gas sensors: Schottky diodes, resistive sensors, electrochemical sensors.

Nanomaterials are employed particularly in electrochemical sensors. Electrochemical gas sensors with sensitive metal oxide coatings like SnO2 save energy and can be integrated into CMOS (Complementary Metal Oxide Silicon) circuits. The use of nanopowders improves sensitivity and robustness of the sensors by the means of ionic conductivity. Different gases like H2, CO2, NOx, CO, CO2 or hydrocarbons can be detected by the variation of the working temperature of the electrode or the electrolyte material. For example, ZrO2 or YSZ are used as electrolyte membranes. Sub μm powders with average particle size 200 nm are used for the production of the electrolyte membranes. Schottky diodes change their electrical conductivity by absorption of gas molecules. They can be used in particular for the detection of hydrogen or hydrocarbons under the harsh space conditions [Pijolat, 2000; Fasoulas, 2001; Hunter 2002].

Sun sensors

Sun sensor on the basis of nanoporous silicon is another application of nanomaterials in space. Decreased reflection losses and improved quantum yields are some advantages of nanoporosity. A prototype sun sensor with use of nanoporous silicon has been developed for a Spanish nanosatellite project by the Instituto Nacional de Técnica Aerospacial [Martin, Palma; 1997].

2.3.8 Aerogels

Aerogels are composed of micro-porous networks made up of interlocking nano-scale filaments (Figure 2.7) and suitable for aerospace applications, since they are low density, highly porous and low thermally conductive. They consist of different materials like silicates or carbon. The low density and porous nature give aerogel the ability for stopping high velocity particles, makes it as a highly efficient thermal barrier, and as a porous medium for the containment of cryogenic fluids.

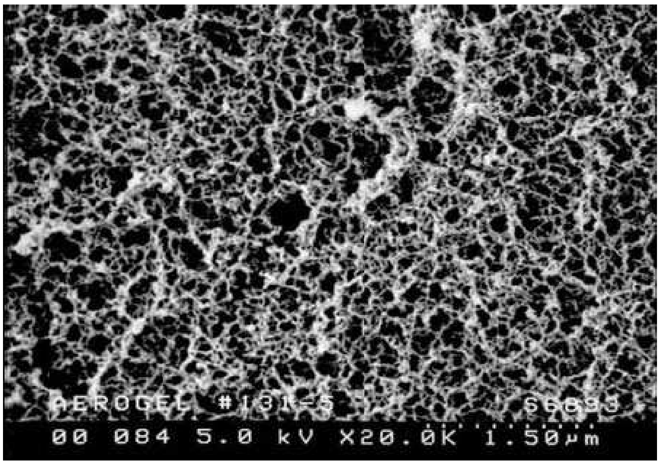


Figure 2.7: Scanning electron micrograph of silica aerogel network- Jones, 2006

Silica aerogel was as the hypervelocity particle capture and return media for the Stardust Mission. Aerogel has been used as the thermal insulation material in the 2003 Mars Exploration Rovers. Mars Exploration Rover (MER) Mission is an ongoing unmanned space mission, started in 2003, to explore the surface and the geology of Mars. Aerogel is critical to their overall design and success in the SCIM (Sample Collection for the Investigation of Mars) and the STEP (Satellite Test of the Equivalence Principle) Missions. Composite materials comprised of silica aerogel and oxide powders are under development for use in a new generation of thermoelectric devices in many future space exploration mission designs. The production of non-silicate and composite aerogels is wanted to extend the range of useful applications in future space exploration projects [Jones, 2006].

2.3.8.1 Aerogel Application for Hypervelocity particle capture

a) The Stardust mission

The Stardust mission was based on the fact that low density aerogel is an excellent hypervelocity particle capture medium and collected samples of cometary coma and interstellar dust and returns them to Earth (Figure 2.8). Aerogel is an excellent hypervelocity particle capture medium, because it is a highly porous material whose microstructure is made up of nano-scale filaments. The Stardust spacecraft was successfully launched in January of 1999 and five years after launch encountered the comet Wild2, coma dust was captured by impact into ultra-low-density silica aerogel. The captured samples were returned to earth in January of 2006. Stardust carried two science investigations: the aerogel dust collector and the CIDA (Cometary and Interstellar Dust Analyzer) [Atkins, 1995].

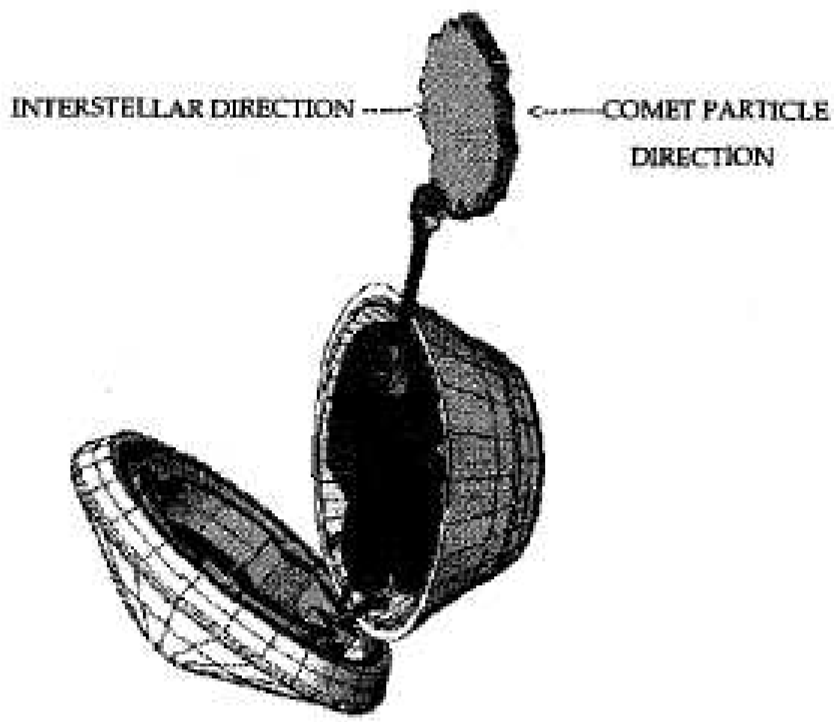


Figure 2.8: Sample Return Capsule with Collector- Atkins, 1995.

Aerogel dust collector exposes blocks of underdense, microporous silica aerogel and other low-density media to the sample flux. The collector consists of modular aluminum cells housing 10 to 20 mm thick aerogel blocks. The cells form a two sided, grid-shaped array that will deploy from the SRC (Sample Return Capsule).

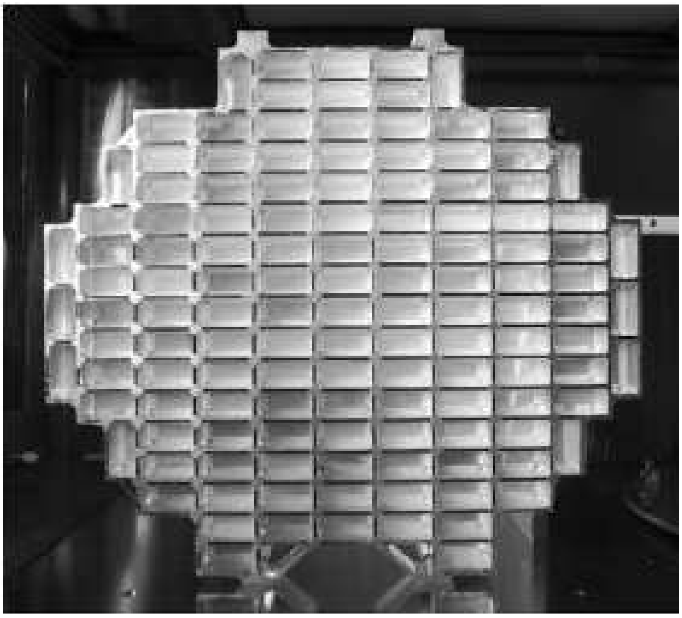


Figure 2.9: Aerogel cells in the Stardust cometary particle collector-NASA

It was so designed that particles from the coma of the comet impacted with the aerogel and embedded themselves in the porous network of the aerogel. After the cometary particles were captured, the aerogel was retracted into the spacecraft and returned to earth. For the collection of the cometary and interstellar particles two grids of aerogel were assembled. These grids were considered so that one grid captured interstellar particles and the other was used to capture cometary particles. Each grid consisted of one hundred and thirty cells of silica aerogel (Figure 2.9).

Due to the fact that the particles impacting the aerogel are micron in size, and the filaments of the aerogel are nanometer in size, the filaments yield to the force exerted by the particles. The kinetic energy of the particles is gradually transferred to the aerogel, as the individual filaments are broken and destroyed, and the particle is slowed and finally stopped, as the kinetic energy is converted to thermal and mechanical energy, largely intact [Jones, 2006].

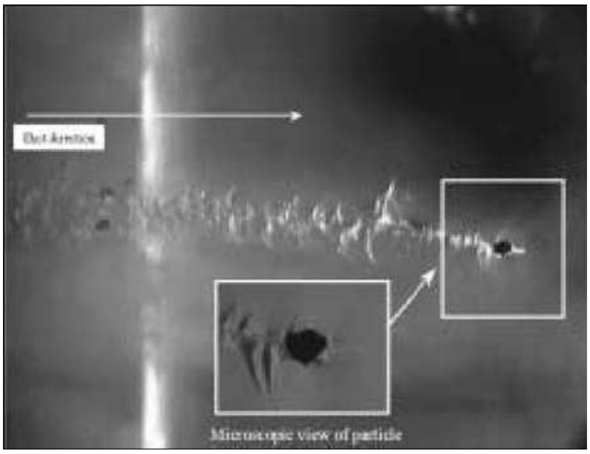


Figure 2.10: Hypervelocity particle as it travels through aerogel network-Jones, 2006.

b) The Sample Collection of the Investigation of Mars

The Sample Collection of the Investigation of Mars (SCIM) Mission was intended to fly a spacecraft through the upper Martian atmosphere to collect dust particles suspended in the atmosphere in aerogel and then to return the sample to earth. It is designed as a low cost, low risk mission for gathering and returning a sample from Mars to earth and based on the technology developed for the Stardust mission.

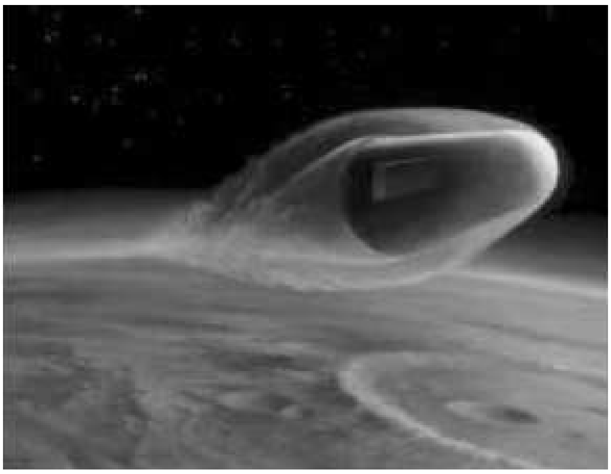


Figure 2.11:
The SCIM spacecraft passing through the upper Martian atmosphere- Jones, 2006

SCIM would similar to the stardust mission aerogel to capture particles in aerogel and then return the aerogel to earth. But, the design of SCIM would experience significant heating during the collection, since SCIM would pass through Mars's atmosphere during the collection phase, and at a very high speed. Because of that the spacecraft is so designed such that the aerogel is housed in two bands around the outer radius of the aeroshell. While the atmosphere flows around the sloped aeroshell and past the aerogel, the particles travel in a straight path into the aerogel.

Another significant difference for the aerogel usage between stardust mission and SCIM is that in SCIM non-silicate aerogel was used to complement the silicate aerogel in the collector. The reason of that is the rich existence of the minerals in silicates that found in our solar system. Non-silicate aerogels like carbon, alumina, titania, germaina, zirconia, and niobia, have suitable low density networks for efficient hypervelocity particle capture. The capturing Martian dust particles by different types of aerogels, the production of this design, the chemical analyses that can be done on the dust particles, can be more extensive. The SCIM Mission was proposed as a 2003 Mars Scout Mission, but was not selected. But the realization of this project in the future is still possible. [Leshin, 2003; Jurewicz, 2002].

2.3.8.2 Aerogel as Thermal Insulation for Mars exploration rovers

Aerogel is being used as the thermal insulation material in the Warm Electronics Boxes (WEB) in the rovers. The thermal insulation keeps the rover electronics at a relatively steady temperature during the approximately 100 °C variations in temperature of Mars between day and night. Because of successful result of the aerogel used in the 1996 Mars Pathfinder rover, Sojourner, a similar aerogel was used in the 2003 rovers. The aerogel was rendered opaque by adding 0.4 % by weight graphite to prevent irradiative thermal transport. Since it is largely transparent to infrared radiation, it can not prevent irradiative thermal transport. Irradiative thermal transport can be prevented by absorbing the thermal energy, by making the aerogel opaque [Jones, 2006].

2.3.8.3 Aerogel Application in Radioisotope Thermoelectric Generators

The Radioisotope Thermoelectric Generators (RTG's) in the two Voyager probes which were launched several decades ago are still in function today. Aerogels are used to channel the thermal energy through the legs and to maintain efficiently the thermal gradient, since they have low thermal conductivity values.

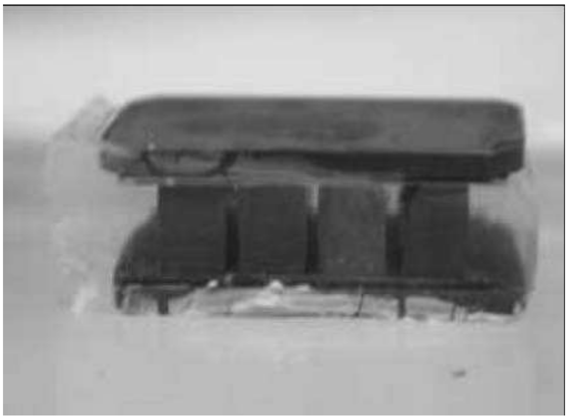


Figure 2.12: Thermoelectric generator module with silica aerogel- Jones, 2006.

For the source of their thermal energy RTG's use a radioisotope and convert this thermal energy into electric energy by employing special materials. They are important for the exploration of the outer solar system because there is not sufficient solar radiation for photovoltaic power generation to be used for energy conversion beyond the orbit of Mars. Since the aerogel can be formed in place, the application of aerogel simplifies the manufacturing process of RTG modules. Aerogel can fill the spaces between the legs and around the module, because the aerogel precursor is a liquid.

However, because of their weak mechanical properties and low durability, they have limitations in aerospace. The mechanical properties of aerogels can be improved by using inorganic and organic material combinations like silicate/Polyurethane. Aerogels can have more applications as high strength ultra-light structure material in space in the future [Leventis, 2002].

Another limitation comes from the processing of conventional aerogels. Supercritical fluid drying which are used in the processing results in high manufacturing costs and limited component size. NASA Glenn Research Center has developed new polymer cross-linked aerogels to avoid these disadvantages. These developed aerogels are thermally insulating (< 40 mW/mK), have low density (< 0.2 g/cm3) and 300 times more flexural strength than conventional aerogels. In addition they can perform 10 times more specific compressive strength than steel.It is equivalent to that of fiber-reinforced composites.

Conventional aerogels consist of silica nanospheres. These individual nanospheres are joined by fragile necks shaping a form like a pearl necklace. Hydroxyl groups are pendant to each silica nanopearl. These hydroxyl groups have been reacted at NASA Glenn Research Center with organic monomers like isocyanates. In this way, conformal coatings can be produced around the nanospheres. This new produced material can be processed without the use of expensive supercritical fluid drying and does not collapse during solvent evaporation. Varied new aerogels have been also developed to obtain more flexibility of the material. In addition, polyimide, epoxy, polystyrene cross-linked silica aerogels are created by the modification chemistry. Polymer aerogels have been also obtained from various metal oxides. Applications of aerogels in space include insulation materials for EVA suits and cryogenic propellant tanks [Meyyappan, Dastoor, 2004].

The use of aerogel in space missions can expand with the development of the types of aerogel available beyond silica, carbon, non-silicate oxides and non-oxides, and with the extending production of silica aerogel.

2.3.9 Magnetic nanocomposites

Magnetic nanocomposites are made of nanoscale magnetic crystallites in an amorphous or crystalline matrix like polymers or silicates. Soft magnetic materials are used for transformers and inductors in electronic components, hard magnetic materials have applications in energy storage, data memories and sensor technology. Nanostructure affects some physical properties like coercivity. Some magnetic nanocomposites are SiO_2 coated cobalt nano-particles, polymers and polyimide-coated Fe nanoparticles. Due to quantum coupling between neighboring nanoparticles, magnetic nanocomposites have a higher permeability, Curie temperature and electrical resistance than conventional ferrite materials. They can detect changes of magnetic field more sensitively and work at a higher temperature range. These properties make possible for space applications the advancement of miniaturized and energy saving microwave antennas, inductors, sensors or data memories for space applications [Wincheski and Namkung, 2000; Jonson, 2001].

3. Nanotechnology for Thermal, Radiation and Impact Protective Shields of Crew Exploration Vehicles and Aeroshells

In the atmospheric reentry process, the space vehicle outside the atmosphere of a planet enters the atmosphere and reaches the surface. Special methods are required to protect the space vehicle against the aerodynamic heating.

3.1 Thermal Protection Systems for Space Vehicles

The main object of a Thermal Protection System (TPS) is to keep excessive heat away from vehicle or its contents and to prevent destroying or damaging. The appropriate TPS depends on the mission of the spacecraft. The temperature capability is a major concern and therefore the goal is to protect the internal components at a minimal weight. Vehicles which function for a short time need a different thermal protection than those vehicles which function for longer periods of time or for re-usability purpose. The thermal protection system must consist of appropriate materials to meet the mission objectives and the design criteria. Mission environment consists of three parts: the launch, the space environment, and if exists, atmospheric re-entry [Guthrie, 2000].

3.1.1 Mission Environment

In the launch environment, combustion, rocket exhaust plume and aerodynamic heating cause extreme induced thermal conditions during liftoff and ascent. Additionally vehicles can experience natural conditions such as wind, rain, hail, lightning strike, and salt water.

Orbit, time of year and solar activity determine the natural environment of space and it includes vacuum, ionizing radiation, spacecraft charging, contamination, degradation due to UV radiation, the existence of atomic oxygen in the upper atmospheric layers, and impact from meteoric debris.

In the re-entry environment, the space vehicle experiences the most severe aerodynamic heating in addition to shock and acoustic loads and it also includes natural conditions such as wind, rain, hail, sand, and dust.

3.1.2 Mechanisms of Thermal Protection

3.1.2.1 Heat sinks

The heat is absorbed by a high thermal conductivity material, distributed quickly and uniformly away from the part of the spacecraft it was designed to protect.

3.1.2.2 Active cooling

Fluids are used in high heat flux areas as a liquid or gaseous heat sink when distributed to hot sections via a cooling loop. This mechanism gives a parasitic weight to the system because of the fluid distribution.

3.1.2.3 Transpiration cooling

In this method, a fluid or gas is ejected through a porous skin into a boundary layer between the heat flux and the surface, and therefore the adiabatic wall temperature of the surface is reduced. Depending on the source of the cooling media, it can be passive or active. In passive cooling, an ablating material is used underneath the porous skin that upon heating sublimes to produce the cooling gas. In active cooling, a fluid is injected from an interior supply vessel through the porous skin.

3.1.2.4 Radiation cooling

The heat flux is reflected by a high emissivity coating on the protected substrate back toward the black body of space. Since the heat transfer rate is proportional to emissivity and the difference between vehicle temperature and space, this method is very effective in orbit.

3.1.2.5 Ablation

This method is used to minimize the total energy that the vehicle absorbs. Ablative cooling occurs when the heat flux changes the state of the surface substrate either by melting, sublimation, or thermal degradation; with the surface mass experiencing the high speed flow. Rather than being conducted to the interior of the vehicle, the heat is expended in a material phase change. On the Apollo Command Module ablative heatshields were used.

3.1.3 Types of Thermal Protection Systems

3.1.3.1 Blanket insulation

Blanket insulation material consists of high purity silica, high-purity alumina fibers, or combination of the two and is a low density, low thermal conductivity material. This material is not strong and can not be applied as a structural material but supplies very effective thermal protection.

3.1.3.2 Tile Insulation

Tile Insulation composed of lightweight, low conductivity fibers like blanket insulation. But, because of processing and coating treatments, it is more resistant to aeromechanical loads. They are good insulators, because by volume they are approximately 90 % voids. Since they are rigid and are composed of low thermal expansion fibers, they must be strain isolated from higher expansion metallic substrates via an aramid fiber felt and RTV silicon. Individual tiles can be replaced, because of their modular structure. Because of that they need gap fillers between them. The tiles used on must be waterproofed using a silicone resin, because of their porous structure.

Typical types of tile insulation:

1) LRSI (Low Temperature Reusable Surface Insulation): Their function is to protect the sections of the space shuttle orbiter that experience maximum temperatures between 371 and 649 °C and they are the white tiles of the orbiter. LRSI tiles on the shuttle consist of 99.8% pure silica fibers and have thickness between 5 – 35 mm. The coating is a combination of silica compounds and aluminum oxide and it gives the tiles their white appearance.

2) HRSI (High Temperature Reusable Surface Insulation): These black-coated shuttle tiles are generally thicker (between 25 –125 mm.) than LRSI tiles, Hence strain isolation is more important for the HRSI tiles. HRSI tiles are coated with a combination of powdered tetrasilicide and borosilicate glass. HRSI and LRSI tiles control the temperature of the shuttle during orbit just by orienting one side or the other towards the sun. HRSI tiles are used in two different densities (0.35 g/cm3 and 0.14 g/cm3). The dense HRSI tiles are more resistant to damage.

3) FRCI (Fibrous Refractory Composite Insulation): This material is made of 20% alumina-borosilicate fibers and 80 % silica fibers. They yield a tile with three times the tensile strength, 38 ° C greater temperature capability and 10% lighter than an HRSI tile. Therefore FRCI has replaced many of the HRSI 0.35 g/cm3 tiles.

3.1.3.3 Ablators

Ablative materials function by absorbing a great amount of heat through a phase change. Charring ablators form a char layer. Char layer acts as an insulator while the material underneath continues to decompose and outgas. The gaseous products from decomposition percolate through the char to cool the surface. The char blocks convection heating and in high heat flux environments, they sublime. Thus, these ablators provide multiple levels of protection. There are two methods by the application of ablators. First method is the application of low temperature ablators. They ablate easily and they are very effective in removing heat. They have high drag coefficients and slow vehicles down dramatically.

Cork, Teflon, Lucite, fiberglass, nylon, and urethane are some of early examples of low temperature ablators. Jupiter missiles used copper, beryllium, and even tungsten and molybdenum blunt nose tips as heat sinks. Scout, the first solid-fuel launch vehicle, launched the United States' first satellite; Discover I, by using cork/fiberglass heatshields and cork insulated fins. One of the Apollo used nylon reinforced with Teflon between fiberglass and cork layers to protect the astronauts.

Today, ingredients of many of the same materials are used as low temperature ablators. For example, the French are using cork phenolic on an Atmospheric Reentry Demonstrator (ARD). It is intended to transport crewmembers back from the International Space Station.13 The Pathfinder used a phenolic honeycomb filled with a cork and silica bead filled epoxy, SLA-561, for the Mars entry heatshield.

Carbon/phenolic and quartz/phenolic are the most significant among the several intermediate temperature ablators. They are frequently used in higher heat flux applications.

The second method is the application of materials that ablate very slowly. These materials ablate at higher temperatures, although they absorb a lot of energy when they ablate. For example, a carbon to carbon double chemical bond requires a lot of thermal energy to break and begin the ablation process. This causes the need for more insulation to protect people and delicate parts. High temperature ablators can retain their shape in extreme environments. With the aid of this high temperature capability designers can develop more slender, lighter vehicles. In addition, these high temperature ablators do not slow the vehicle down as quickly during reentry, so they are both faster and more accurate. The most widely used of these high temperature ablators are 3-D and 4-D carbon-carbon composites.

3.1.4 Hot Structures

Hot structures can maintain their aerodynamic load bearing capabilities at high temperatures. The selection criterion of them is based on expected temperature regime and mechanical loads. Hot structures require insulation to protect underlying components. The temperature capabilities of materials for hot structures are showed in the Figure 3.1; carbon-carbon composites have the highest temperature capability of all material systems.

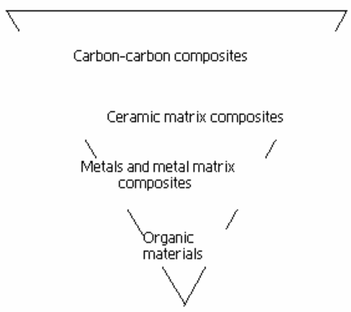


Figure 3.1: The temperature capabilities of materials- illustrated by Pelin Berik.

Carbon fiber in a carbon matrix composes carbon-carbon composites. A combination of fiber properties determines the mechanical and thermal properties, matrix properties, and processing effects. Carbon-Carbon becomes stronger and stiffer at elevated temperatures. But their main disadvantage is their poor resistance to oxidation. They begin to oxidize in air at around 500° C. In applications such as the space shuttle nosecap coated C-C is used. Reinforced Carbon-Carbon (RCC) is C-C with a silicon carbide conversion coating and a tetraethylorthosilicate overcoat to retard oxidation. A low conductivity rayon-based fiber is used in RCC and exists on the wing leading edges and the area around the external tank attachment point. In the nosecap area, RCC uses its high emissivity to radiate heat from the hot stagnation region to cooler areas of the hollow nosecap to reduce the stagnation temperature.

Ceramic matrix composites (CMC) include carbon-reinforced silicon carbide (C/SiC) and silicon carbide reinforced silicon carbide (SiC/SiC). C/SiC has the superior strength and stiffness at elevated temperatures of carbon fibers with a more oxidation resistant matrix. In the situations where oxidation resistance and high temperature capability are critical, SiC/SiC materials are used. Some of composite materials systems that have been observed for hot structures are SiC/Si3N4, SiC/LAS, and Al2O3/Al2O3.

For example, Hermes, the French version of the space shuttle, was designed with C/SiC nosecaps and leading edges before the program was cancelled. The ARD (Atmospheric Reentry Demonstrator) which was shaped similarly to the Apollo capsule, have four CMC tiles in the large blunt heatshield.

NASA-AMES examined recently ZrB2/SiC, HfB2/SiC and ZrB2/SiC/C materials for nose tip application or a slender leading edge to reduce vehicle drag and increase payload capability.

3.2 Crew Exploration Vehicle, Aeroshell, Trips

Future exploration missions require long durations; bring more exposure to radiation, orbital debris and micro-meteors. The damage risk to the space vehicle and human safety will also consequently increase. With flight time linearly growing exposure leads to development of more durable and stronger space vehicles. One of the new space exploration plans of NASA is the development of Crew Exploration Vehicle by the means of atmospheric re-entry situation for the return from the Moon and the Mars. Re-entry heating dates of CEV are 10 and 40 times more effective than values on the wing leading edge of the Space Shuttle. The development of a single shield is achieved by advances in nanotechnology. The developed single shield provides more performance by the means of mass reduction and improved safety against radiation, debris and meteors. The design and selection of advanced thermal materials is dependent on the aerothermal environment. Existing methods can predict laminar windward heating to within 20 % for only a limited range of conditions like Earth reentries from low Earth orbit and low velocity ballistic entries at Mars. However, Lunar and Mars return missions, and outer planet probe missions, experience much higher entry velocities. When a space vehicle enters a planet's atmosphere, the Entry System protects the payload, human or robotic, from the extreme environments experienced during entry.

Trips

An application of nanomaterials in Thermal, Radiation, and Impact Protective Shields (TRIPS) has been developed by NASA Ames Research Center. The thermal protection system of the CEV protects the vehicle from intensive heating and supplies radiation protection. For radiation shielding, materials with high carbon and hydrogen concentration are mostly suitable. For example, in radiation shield designs polyethylene is preferred. The reason of that is the reduction of secondary radiation during the collision of high-speed galactic cosmic rays and solar particle events. A fully dense carbon phenol can provide 50-70 percent of the radiation shielding and required thermal protection during a year that is needed for a mission around Mars.

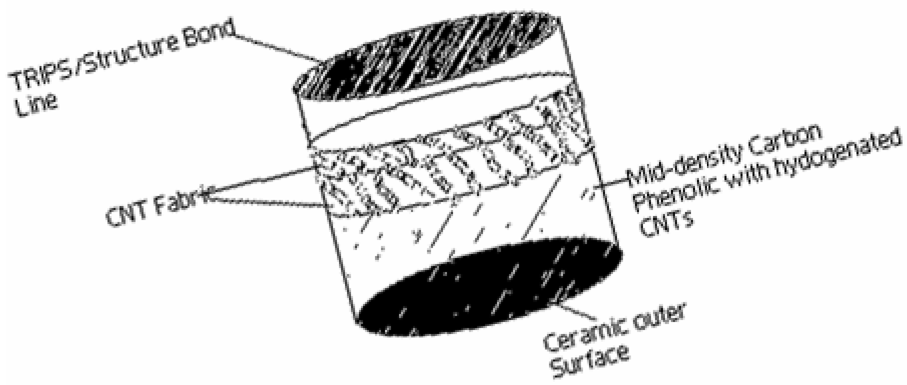


Figure 3.2: Trips-re-illustrated by Pelin Berik.

The Trips contains carbonaceous ablators such as carbon phenolic, phenolic nylon, hydrogenated carbon nanotubes, the PICA ablative carbon tile (phenolic impregnated carbonaceous ablator) which enabled the Stardust mission and recently collected comet dust (Figure 3.2). Stardust represented the first flight of PICA. Another Ames invention, SIRCA (Silicon Impregnated Reusable Ceramic Ablator) ablative tile enhanced the TPS design of the Mars/Pathfinder, and Mars Exploration Rover vehicles. It was also the baseline material for the leading edges and nose-cap of the X-34 vehicle. Ceramic outer shell breaks up micrometeors and orbital debris strikes. The design, manufacture and test of the thermal protection systems (TPS) used on the Mars Exploration Rover aeroshell structure is supported by Ames Research Center. The aeroshell (Figure 3.3) forms a protective covering during the mission. The aeroshell consists of two main parts: the heatshield which protects from the intense heat from entry into the Martian atmosphere and aerodynamically acts as the first "brake" for the spacecraft, and the backshell which carries the parachute and several components used during later stages of entry, descent, and landing, including. By the use of NASA Ames' Arc Jet complex aeroshell TPS materials are qualified in a simulated high-temperature entry environment. Ames-manufactured TPS material SIRCA (Silicone Impregnated Reusable Ceramic Ablator) was attached to the back part of the aeroshell, called the Backshell Interface Plate (BIP). SIRCA protects the three Transverse Impulse Rocket Systems (TIRS) located on the sides of the aeroshell.

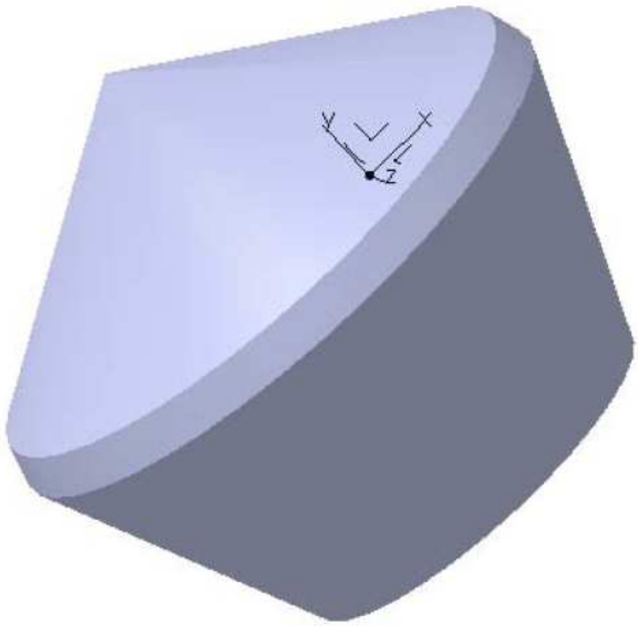


Figure 3.3: Aeroshell-illustrated by Pelin Berik.

Rigid aerocapture aeroshells can have several shapes, depending on the aerodynamic characteristics needed. Three typical shapes are used generally in aerocapture: the sphere-cone, biconic, and ellipsled. The sphere cone is designed a low L/D shape, while the ellipsled and biconic are designed mid L/D shapes. The specific shape used is a function of aerodynamic and internal packaging volume requirements and depends on the mission trajectory and destination atmosphere [Dyke, Hrinda; 2004].

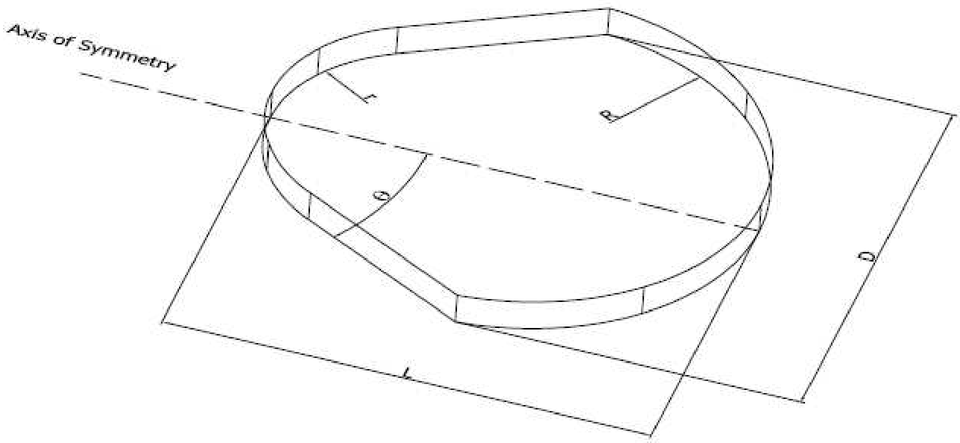


Figure 3.4: Schematic of Aeroshell-illustrated by Pelin Berik.

Aeroshells are the best designed containers for the protection of probes. Their shape helps the aeroshell to pass through the air more easily and makes it aerodynamic. The probes are placed in their aeroshells so that most of the weight is in the aeroshell nose. Aeroshell always straightens itself out and lands nose side down. This feature is important, because the nose side of the aeroshell is covered with a heatshield. Heatshield protects the probes from the heat of entry and must be pointed along the direction of travel.

4. Space Elevator

A space elevator consists of a cable attached to the Earth surface to transport astronauts and scientific research materials like spacecraft, instruments, satellites, and raw materials into orbit or further [Artsutanov, 1960]. It is proposed that if the cable is long enough, for example around 150 000 km, a value which can be reduced by a counterweight, the centrifugal forces exceeds the gravity of the cable, so that the cable can work under tension [Pearson, 1975]. The elevator could stay fixed geosynchronously. When the climbers are once sent far enough, then they can be accelerated by the Earth's rotational energy.

In the space elevator design the most important part is the cable. The cable must have a very high strength and low density. It is considered that the cable has a constant section and a vanishing tension at the planet surface and the maximum stress at the geosynchronous orbit (Figure 4.2) - 63 GPa for the Earth- if for the cable the low carbon density (1300 Kg/m^3) is considered. A high strength has been observed during by Yu executed tensile tests of ropes composed by multiwalled carbon nanotube and single walled carbon nanotubes with an ideal strength of about 100 GPa [Yu, 2000a-b]. It must be noted that steel has a density of 7900 Kg/m^3 and strength of approximately 5 GPa. The maximum stress that can be expected in the cable is 383 GPa. This value is much higher than its strength.

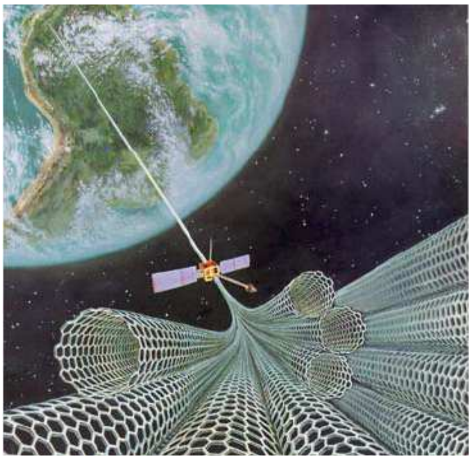


Figure 4.1: Space elevator- M. Meyyappan

For an optimized cable design a uniform tensile stress profile is more important than a constant cross-section area. The cable can be produced of any material by simply using a large enough taper ratio. Taper ratio is the maximum cross section area (at GEO, section 8.1) over its minimum value (at the Earth's surface). For steel taper ratio is 10^{33}, for carbon nanotubes is only 1.9. The mass of the cable is proportional to the taper ratio. Therefore the feasibility of the space elevator is currently possible only with the use of nanotubes [Edwards, 2000; Edwards 2003].

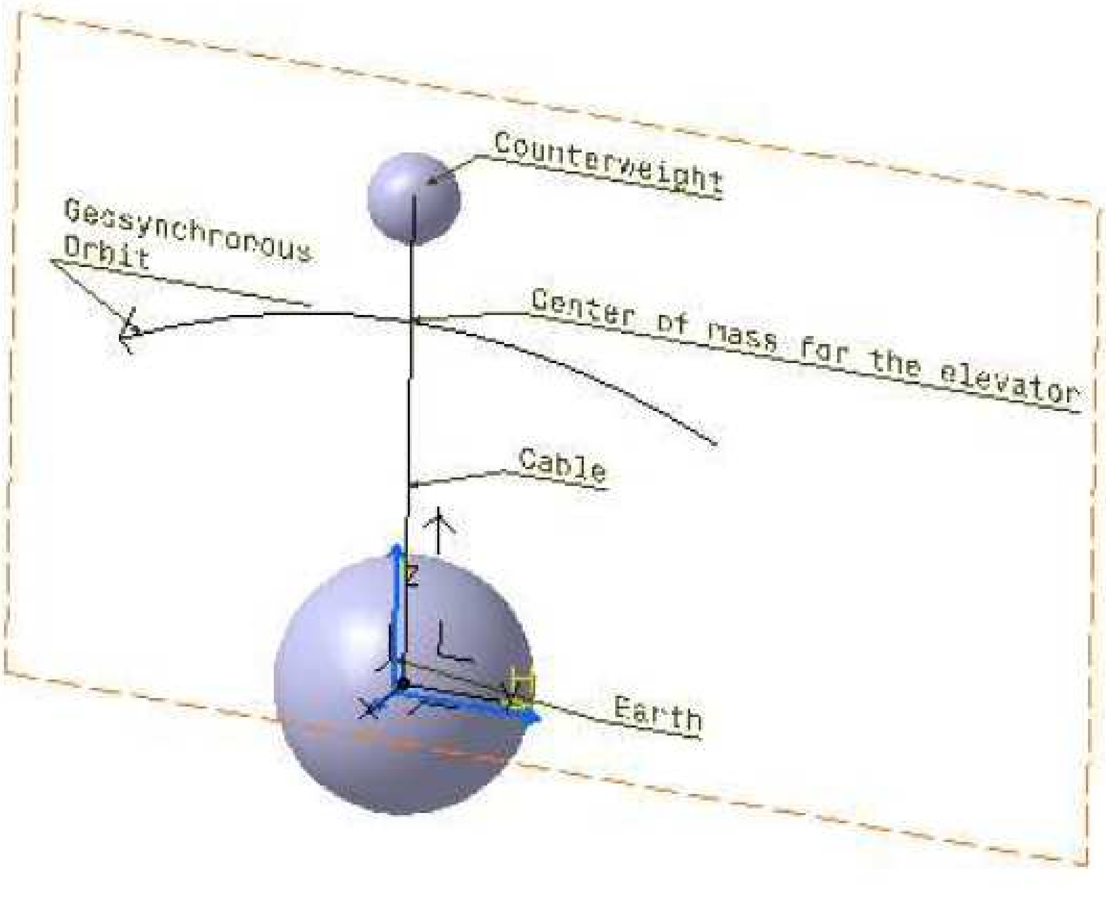


Figure 4.2: Space Elevator Model: illustrated by Pelin Berik.

There are possible erosion problems (Figure 4.3) with the cable that can occur: lightning, meteors, space debris, low-Earth-orbit, wind, atomic oxygen, electromagnetic fields, radiation, and erosion of cable by sulferic acid droplets in the upper atmosphere.

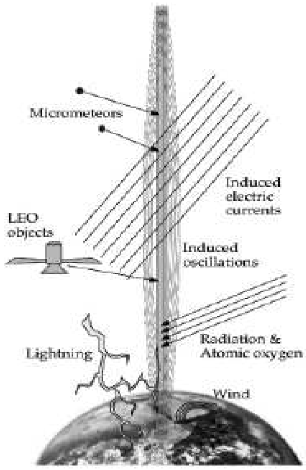


Figure 4.3: Possible erosion problems.

For possible space elevator construction the time frame is assumed to be more than 50 years, in the latter half of the 21st Century.

5. Solar Sail

Solar sail is a form of spacecraft propulsion. It uses the sun as light source; unlike rockets they require no fuel. Solar collectors, temperature-control panels and sun shades are some solar sails, they help ordinary spacecraft and satellites make minor corrections to their attitude without using fuel. This conserves fuel that would otherwise be used for maneuvering and attitude control. Solar sails expand our capabilities by allowing us to explore our solar system and beyond the solar system, to develop our knowledge of the interstellar medium. Solar sail is an appropriate candidate for an interstellar probe propulsion system. There are no solar sails that have been successfully deployed as primary propulsion systems, but research and design studies are continuing. The only solar sail tested in space was the Russian sail Znamia 2, a 20 m diameter rotating round sail. It was deployed from an automatic cargo Progress re-supply vehicle. Experimental deployment took three minutes. The sail remained attached to the Progress vehicle to provide the attitude control. In February 1999 the 25-m-dia Znamya 2.5 space reflector experiment failed.

The conceptual design that a spacecraft could be propelled without fuel by using the pressure of sunlight was proposed firstly by Tsander in 1924. A solar sail functions by the pressure of sunlight on a large, lightweight reflective surface. Garwin in 1958 and Tsu in 1959 have analyzed the solar-sail concept and concluded that it could be made practical. The application of solar sails has been considered for Mars missions [Staehle 1981], Mercury orbiters, comet and asteroid rendezvous [Friedman, 1978], and for interstellar probes [Matloff 1984A, 1984B; Mallove and Matloff 1989].

The technology utilizes solar photons, i.e. sunlight. Solar photons are reflected off giant, mirror-like sails made of lightweight, reflective material 40 to 100 times thinner than a piece of writing paper. The continuous photonic pressure gives enough thrust to perform maneuvers, such as hovering at a fixed point in space and rotating the space vehicle’s plane of orbit. This would normally require too much propellant for conventional rocket systems. This by the sun supplied propulsive energy makes solar sails independent from onboard propellant, therefore payload mass is also reduced.

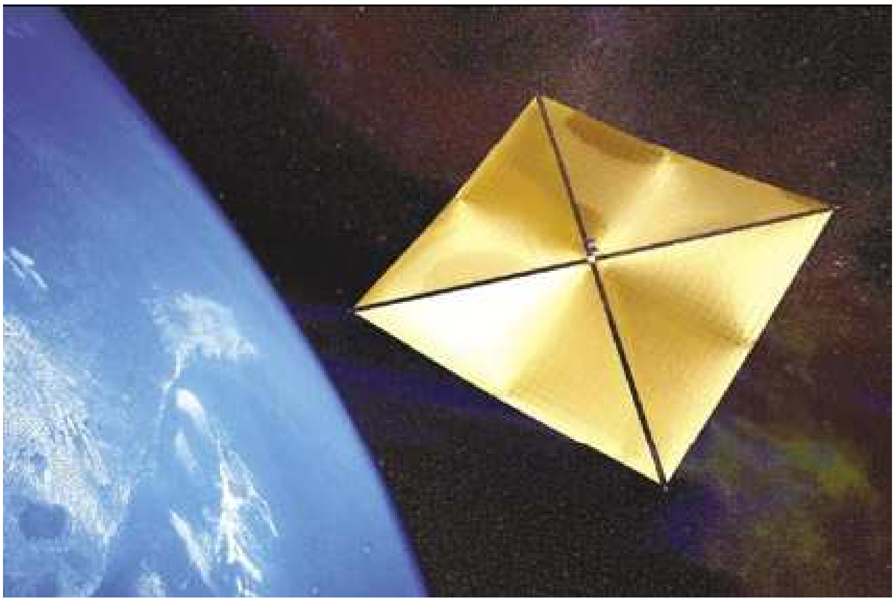


Figure 5.1: Solar sail-NASA

A solar sail composed of usually a thin sheet of plastic (typically Mylar) with a reflective metal (typically aluminum) layer. The most common material in current designs is aluminized µ2m Kapton film. A new carbon fiber material that might be useful for solar sails has been developed by Energy Science Laboratories in 2000.

There are some theoretical studies about using nanotube mesh weaves for the production of solar sails. But, these materials have only been produced in laboratory conditions, and by the means of manufacturing they are not yet available on an industrial scale.

Investigated Sail Designs

The highest thrust-to-mass solar sail known were designed by Eric Drexler. He designed a sail with reflective panels of thin aluminum film (30 to 100 nanometers thick). The design would have to be continually under slight thrust. Samples were made and handled of the film in the laboratory. Since the material is too delicate for folding, launch, and deployment, the design was based on space-based production of the film panels. Sails in this class would offer higher accelerations than designs based on deployable plastic films.

Solar sail propulsion concept is still being developed by NASA scientists at Marshall Space Flight Center. The Center executes the In-Space Propulsion Technology Program on behalf of NASA's Science Mission Directorate in Washington.

The NASA sail design varies in size from tens of meters up to 1000 meters in diameter, according to its mission destination, and typically is shaped like a square. They consist of flat, smooth material covered with a reflective coating and supported by lightweight structures attached to a central hub. Near-term sails will be based aluminized Mylar—a strong, thin polyester film—or CP-1, a space-rated insulating material. Both materials have been previously proven and flown in space. Other designs might use a meshwork of interlocking carbon fibers.

Three basic types of near-term solar sail designs are three-axis stabilized square sails, heliogyro sails and spinning disc sails (Figure 5.2). Heliogyro and spinning disc sails are similarly spin during their travel in space; but, they are structurally different [NASA FS, 2005].

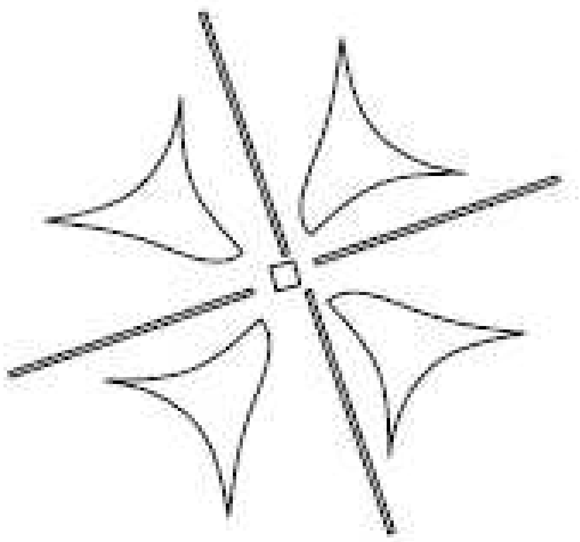
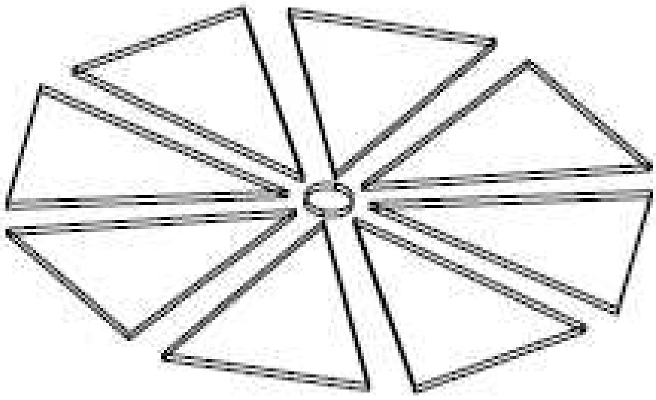
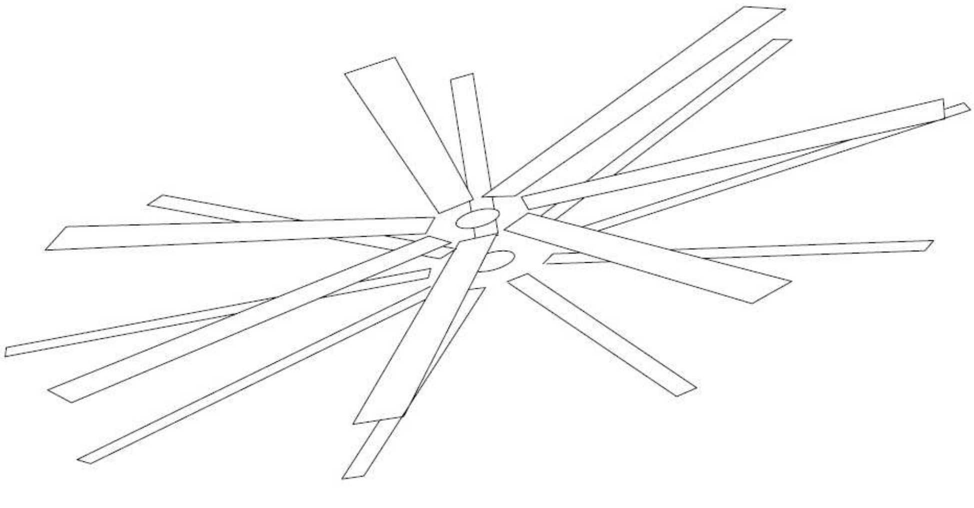


Figure 5.2: a) Square Sail-Pelin Berik



b) Spinning disc sail.



c) Heliogyro sail

An alternative to the classical idea of solar sails is to make the sail from high strength carbon fiber, assembled with a controlled porosity to reduce the mass, and laid out in a web of tension lines (Figure 5.3).In this concept-design the lightweight reflector made from carbon nanotubes, is supported by tendons. The tendons carry tension loads and are joined so that, they are creating nodes. This concept with carbon nanotubes give the strongest yet lightest-weight structure for sails with the greatest temperature range [Wright, 1992].

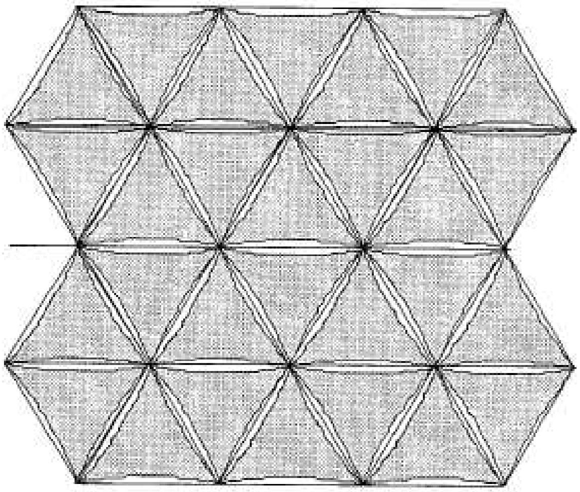


Figure 5.3: Ultra light-weight sail concept- [Wright, 1992].

The amount of power that can be radiated by the sail is proportional to the maximum temperature (Tm) raised to the fourth power. The maximum obtainable acceleration is equal to the maximum force per unit area divided by the sail mass per unit area, which is equal to the mass density (r) times the thickness. If we compare sails of equal thickness, the Figure of merit for acceleration of the sail, Z, is equal to the produce of the fourth power of the maximum temperature divided by the density:

Z = Tm4/r (4)

The maximum temperature Tm and the density r are thus the critical parameters to selecting the sail material [Landis, 1999].

Matloff has noted that the limitation on the final velocity of a solar-sail is due to the heating of the sail [Matloff, 1984A]. Dielectric films with excellent high-temperature properties, with very high emissivity and low absorption, which minimizes the heating, are possible candidates for solar sails. But a disadvantage of dielectric films is that they are less effective for solar reflectance, since the thickness cannot be tuned to optimize reflectance at a single wavelength. Therefore, the reflectance over the solar spectrum decreases.

However, due to the low absorption and high emissivity of dielectric films, they outperform metal films for high power densities; this means they are suitable for missions close to the sun. Physical properties and reflectivity of some possible dielectric nanomaterials are showed in the table 1 and 2 below. Figure of merit Z is compared to aluminum, with density of 2.7 and melting temperature of 940K.

Material	Max Temp. (°C)	Density (gr/cm3)	Z (referenced to Al)
Oxides			
Silicon dioxide	1600	2.7	8.4
Alumina (Al2O3)	2327	3.96	25.6
Tantalum Pentoxide	1870	8.75	4.8
Zirconium dioxide	2715	5.5	34.2
Semiconductors			
Silicon Carbide	2000	3.17	17.5
Zinc sulfide	450	3.9	0.36

Table 1: Properties of Representative Refractory Dielectric Materials

Material	Reflectivity
Oxides	
Alumina (Al2O3)	26%
Tantalum Pentoxide	52%
Zirconium dioxide	42%
Semiconductors	
Silicon Carbide	56%
Zinc sulfide	48%

Table 2: Reflectivity of some dielectric nanomaterials for solar sail construction.

Another new material for the application on solar sails is microtruss fabric. It is a porous, thick fabric with discontinuous carbon fibers joined to one another along nodes. They can be used at temperatures over 1800 K. Continuous rolls of 1-m-wide microtruss fabric consists of of 1 μm-10 μm fibers, nanotube fibers and aluminum reflective film. They are assembled into sail segments. Sail segments are supported by a net of 100 μm carbon ropes (Figure 5.4, 5.5). Nanotubes provide a high emissivity surface [Garner, 2000].

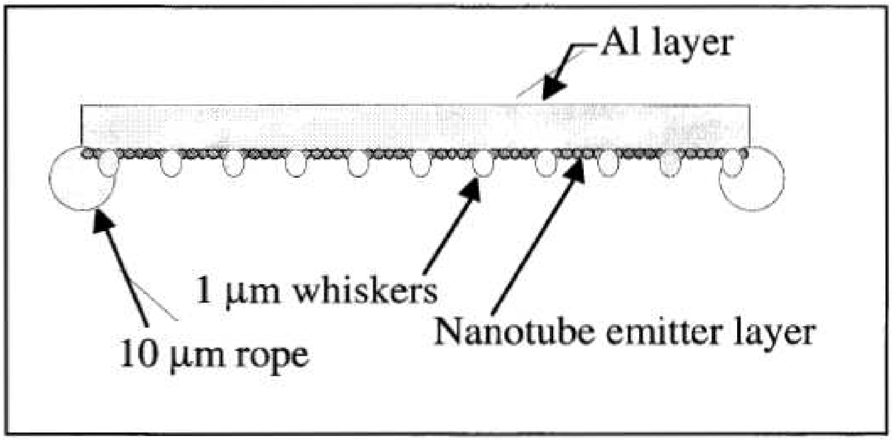


Figure 5.4: Diagram of carbon fabric-[Garner, 2000].

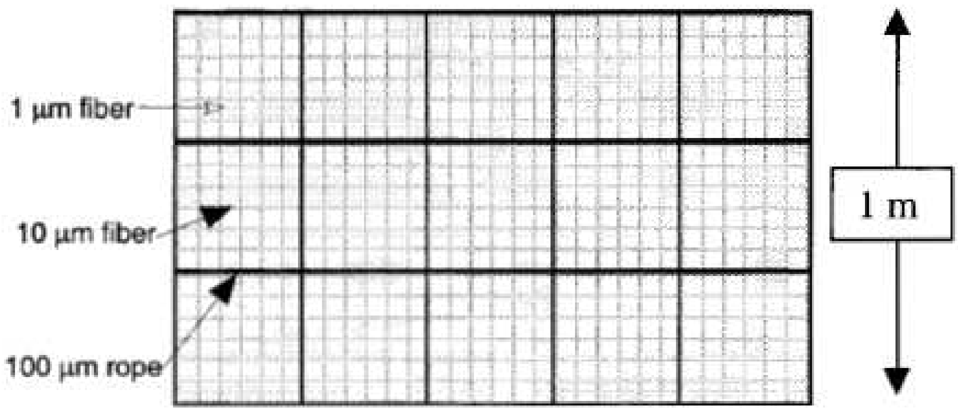


Figure 5.5: Top view of a continuous segment of sail material-[Garner, 2000].

6. AFM on Mars

Observation of solids and dust particles in space with nanoscale resolution has been achieved without a sample transport to earth by the development of scanning probe devices. AFM (Atomic Force Microscopy) has been used for the analysis of Mars Dust and also for Mars meteoroid. Soil and dust particles on the Mars surface are investigated by scanning probe devices.

The possible existence of primitive fossilized organisms within carbonate globules has been found on Mars meteorite (ALH84001) by AFM. Images of possible microfossils provided the evidence for primitive life (Figure 6.1). AFM has imaged particularly a range of proteins, nucleic acids and cells [Steel, 1997].

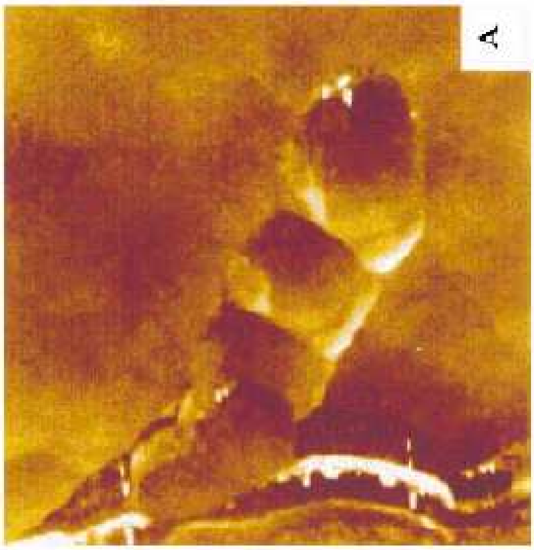


Figure 6.1: AFM image- Martian meteorite- nanofossils-[Steel, 1997].

A Swiss consortium developed an AFM device for the Mars Surveyor mission of NASA [Gautsch, 2000]. Eight microprobes were installed on the AFM chip (Figure 6.2) to increase the dependability of the system. But one cantilever is used for the measurements. For the adaptation to the space conditions the components of the AFM have been specially designed.

Mars is the planet with the most hospitable climate in the solar system after Earth. Channels and other geologic features give the evidence of existence of liquid water on the surface of Mars. The temperature is now too low and the atmosphere too thin for liquid water to exist at the surface. Several questions lead us to explore the Mars such as the change of climate, the possible existence of bacteria in the subsurface today. Water is an important element because it is the evidence of the life. The main aim of NASA Exploration on other planets in the solar system and beyond is the search for life.

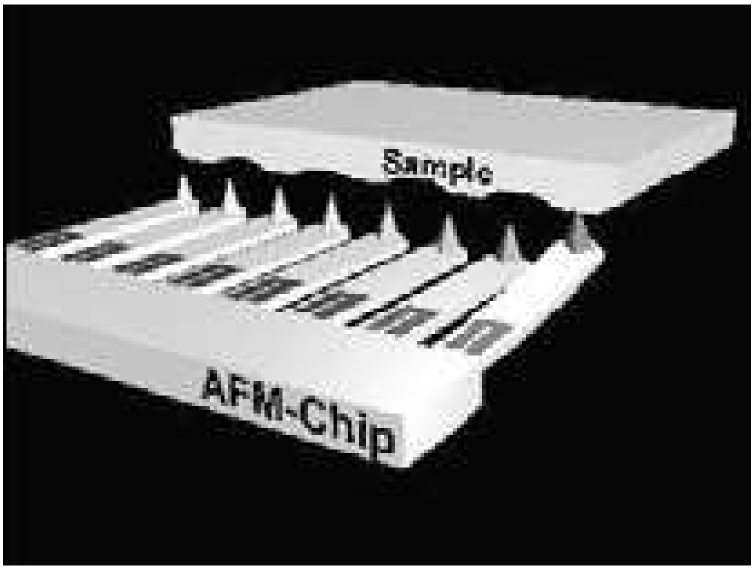


Figure 6.2: AFM on Mars-NASA.

NASA's Mars surveyor Lander intended to realize several in-situ experiments on Mars in 2001, was ready to be launched, but was cancelled due to the back to back loss of two NASA missions in the end of 1999, Mars climate Orbiter (MCO) and Mars Polar Lander (MPL).Today, a new mission, called Phoenix gives the opportunity to send an AFM on Mars in 2007.

The nanoscale resolution AFM on Mars produces 3-D images of individual soil particles and their surface texture, and also focuses on areas of larger particles in detail. The robotic arm will transfer samples into the spacecraft from to the microscopes via individual substrates. The cantilever-based Atomic Force Microscopy technology provides also information about the sample such as roughness and hardness and is a very useful tool for planetary exploration.

The AFM was tested on a lunar soil to determine the AFMs ability to define particle shapes, sizes and grain-surface textures and to prepare AFM for the Mars 01 mission. The test materials were the Apollo 17 soil 79221(Figure 6.3) [Anderson, 2001].

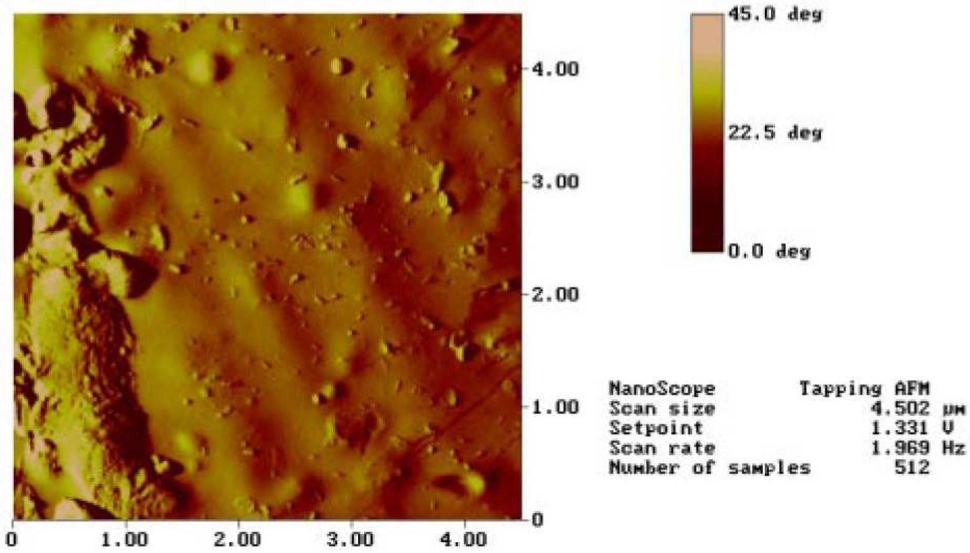


Figure 6.3: AFM image of lunar soil with small particles- Anderson

The aim of AFM on Mars is to know the geologic history and biological potential of the Mars by analyzing detail structure of soil and water ice samples. These microscopes can detect hydrous and clay minerals and indicate past liquid water in the Martian arctic. The atomic force microscope will provide sample images down to 10 nanometers. It is the smallest scale ever examined on Mars. The AFM creates a very small-scale topographic map showing the detailed structure of soil and ice grains (Figure 6.4). An AFM can operate in almost any environment, such as air, dry nitrogen, high vacuum, high pressures or liquids.

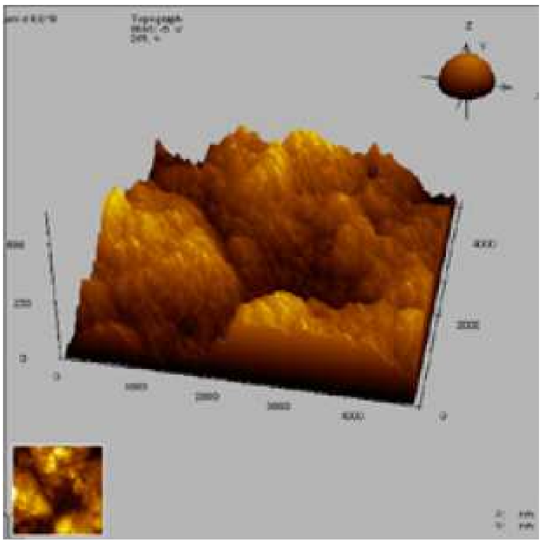


Figure 6.4: AFM image of Mars sand-M.Meyyapan.

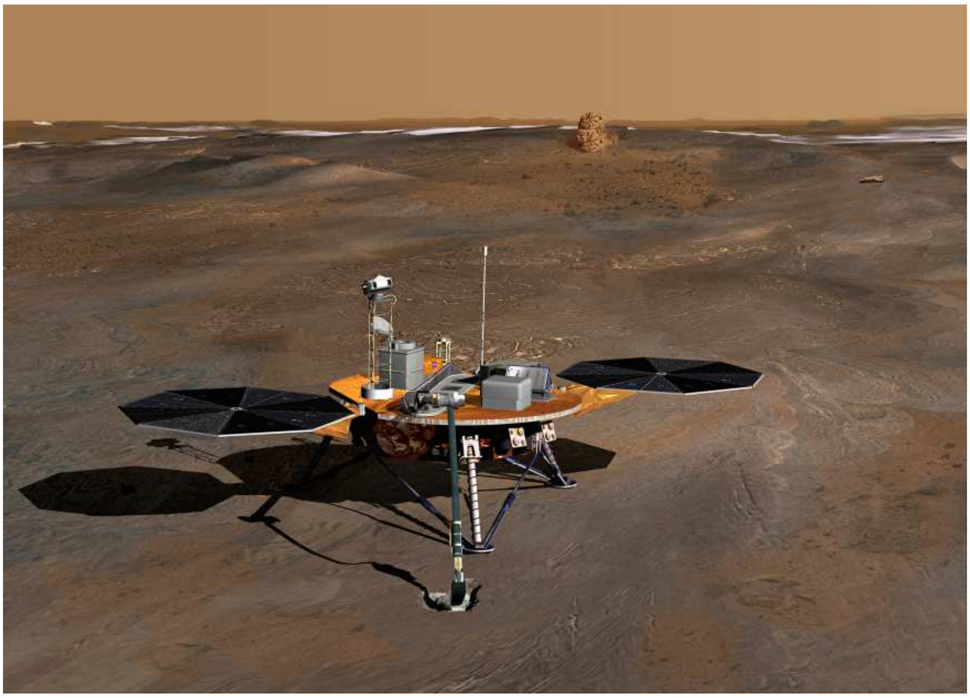


Figure 6.5: The Phoenix Lander that will be sent to Mars in 2007 as NASA's first Scout mission. IMT will have a small Atomic Force Microscope onboard-NASA

The Phoenix Lander is the first Mars Scout mission to study the icy northern plains of the planet (Figure 6.5). With the Phoenix mission, signatures of potential life and for signs of frozen water will be searched. A number of scientific instruments will be carried to analyze the soil and dust by the use of a robotic arm to dig a meter deep into the soil. This procedure shows whether the surface soil has a different history to the soil a meter below and gives us clues about how the Martian climate has changed in this region over the last several million years. Understanding the nature of the dust and surface soil is very important for the safety of future explorers. Martian dust can be a significant hazard to future human explorers.

Mars has no liquid water on its surface. But, large amounts of subsurface water-ice in the northern arctic plains have been showed by the discoveries made by the Mars Odyssey Orbiter in 2002. The target of Phoenix is this region (Figure 6.6). A robotic arm digs through the protective top soil layer to the water-ice below, and for the analysis it brings both soil and water-ice to the lander platform.

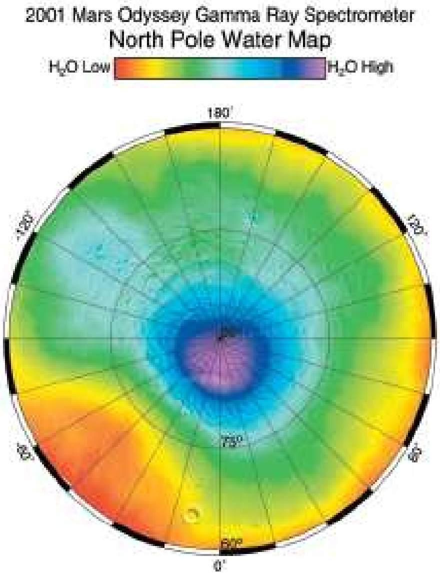


Figure 6.6: North Pole Water Map-NASA

The long-term goals of this program:

- determine the existence of the life on Mars in the past,
- learn about the climate of Mars,
- learn about of Mars, and
- a pre-level preparation for Human Mars mission.

Currently no liquid water exists on the surface of Mars, but Mars Global Surveyor, Odyssey, and Exploration Rover missions suggest that water once flowed in canyons and persisted in shallow lakes billions of years ago. Phoenix will probe the history of liquid water in the 100,000 years scope. One idea suggests that liquid water flows underneath a protective layer of snow.

Mars AFM for the Phoenix mission will find ice or signs of life in May 2008. Although the purpose of the Phoenix mission is not looking for life, we will be able to also learn about the existence of fossils in the soil.

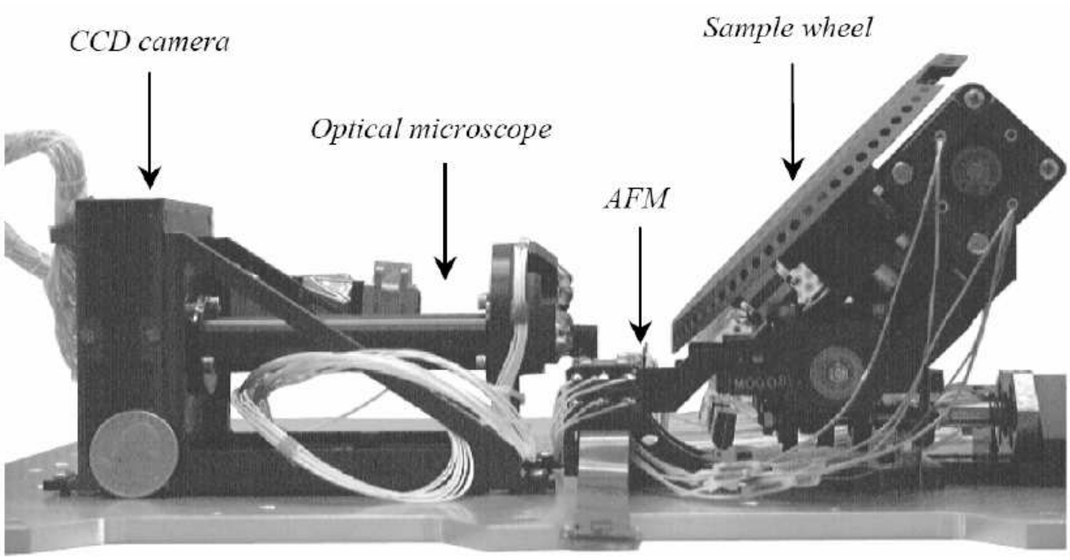


Figure 6.7: Phoenix microscopy station.

A sequence of task is sent from Earth via the Orbiter to the Lander computer on Mars for each experiment. Then the tasks run autonomously. A robot arm scoop the Martian soil containing water ice and then load on to a sample plate. The sample wheel is rotated by 180 degrees and approached to within the scan range of the AFM (Figure 6.7). The electronics moves the scan head; it makes an image of the sample with the selected cantilever. The images are stored on the Lander computer and they are sent to Earth [NASA Technical Report, EP-2006-07-434-HQ].

7. Nanorobotics in Space

Nanorobots represent any smart structure capable of actuation, sensing, signaling, information processing, intelligence, and swarm behavior at nano scale [Ummat, 2004]. Nano-robots are composed of nano-scale components.

Nanorobotics can be divided into two main areas [Requicha, 1999; 2003].The first area includes the studies about the design, simulation, control, and coordination of robots with nanoscale dimensions, i.e., nanorobots. Nanorobots are made of assemblies of nanoscale components with individual dimensions ranging approximately between 1 to 100 nm and they are objects with overall dimensions at or below the micrometer range. Because of the difficulties in producing such devices, the research conducted in this area remains theoretical at the present.

The second area includes the studies about the manipulation and/or assembly of nanoscale components with macroscale instruments or robots like nanomanipulators. Nanomanipulation and nanoassembly have an important in the development of artificial nanorobots. Manipulation at the nanoscale is still under development [Sitti, 2001].

7.1 The Autonomous Nano-Technology Swarm (ANTS) Concept Mission for the Exploration of the Asteroid Belt

The Asteroid Belt is a region between Mars and Jupiter where a greatest concentration of asteroids with diameters of greater than 1 kilometer can be found. Exploration of this region will give important information about the origin and evolution of the solar system. Transportation to asteroids at low costs requires very small spacecrafts few consumables.

Future space exploration missions will use intelligent swarm technologies, enabling spacecraft to go where manned missions and traditional spacecraft cannot. Autonomous intelligent swarms can provide flexibility; perform more and different kinds of operations than traditional single satellite or vehicle missions. They also have complex interactions and behaviors. ANTS is a concept NASA mission. One of its sub-missions, the Prospecting ANTS Mission (PAM) is a long-term mission concept for 2020-2025 involving individual spacecraft agents that are optimized for the exploration of the asteroid belt. This ANTS mission consists of swarms of autonomous Pico-class satellites of approximately 1kg. They search the asteroid belt for asteroids with specific characteristics. Approximately 1,000 spacecraft will be involved in the mission. They travel using solar sails (Figure 7.2) to a point in space, called Lagrangian, where gravitational forces on small objects are negligible. Spacecraft will be launched into the asteroid belt. As much as 60 to 70 percent of them will be lost during the mission, because of collisions with each other or with an asteroid.

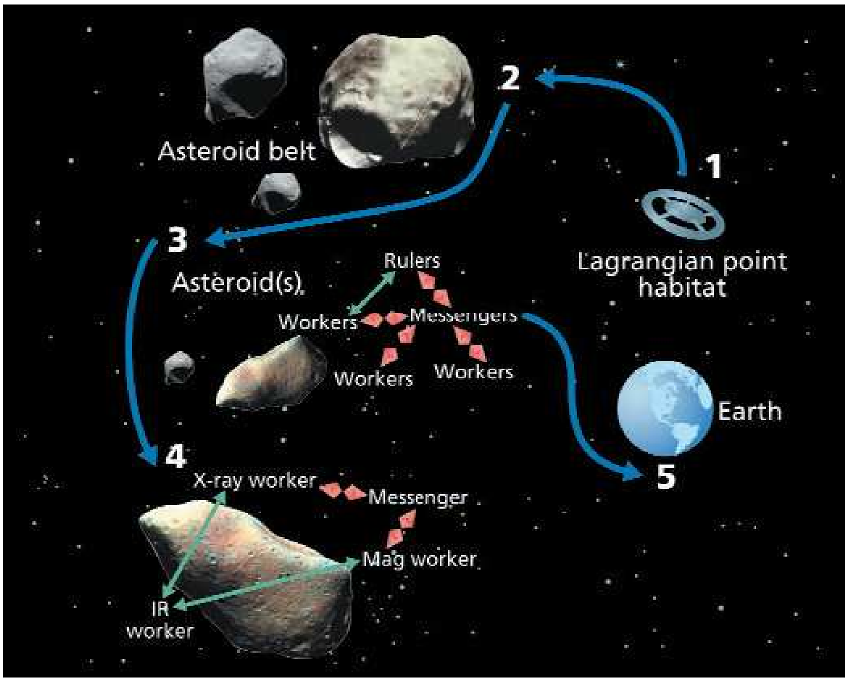


Figure 7.1: Ants concept mission- [Hinchey, 2006].

The swarms use social insect type of artificial intelligence. They are autonomous, with a hierarchical intelligence shared by all members of ANTS. They fly using solar sails from Earth to the targets in the asteroid belt. Data transmission to Earth occurs via returning swarms. Approximately 80 percent of the spacecraft own instrument capability such as magnetometer, x-ray sensor, gamma-ray sensor, visible/IR sensor, and neutral mass spectrometer in order to evaluate each asteroid. The ruler will coordinate workers. Workers have its individual instrument to collect data on specific asteroids and give this information to the ruler. Ruler will determine which asteroids will be examining further. A rough model will be created by other spacecraft for maneuvering around the asteroid. Other groups of spacecraft will finish mapping the asteroid to make a complete model [Curtis, 2000; Hinchey, 2006].

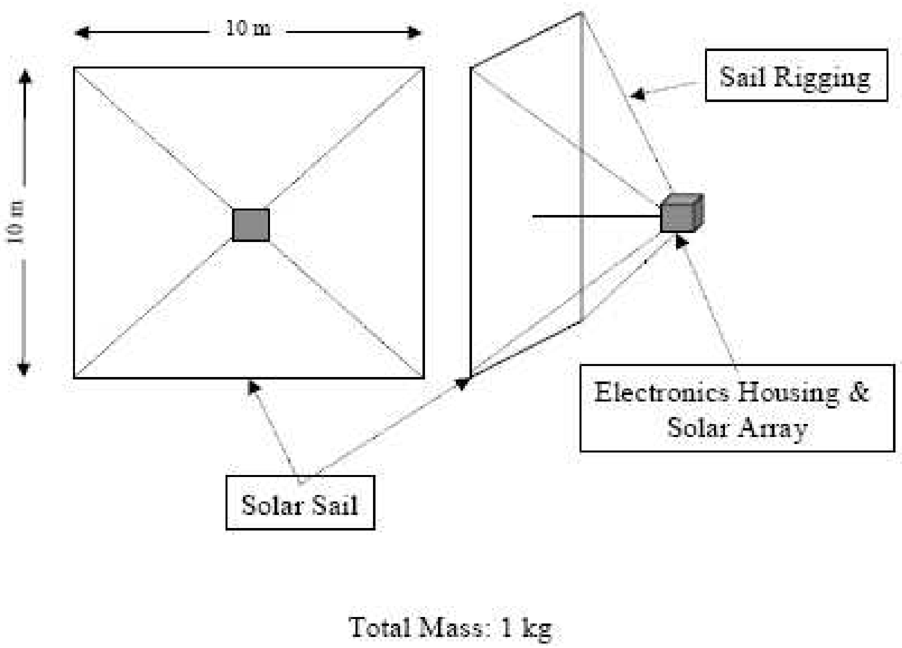


Figure 7.2: Schematic Ants-[Curtis, 2000].

7.2 ANTS for the Lunar or Mars Surface Applications

The aim of this ANTS submission is to support of near term human activities on the Moon or Mars. An ANTS craft is a multi-tetrahedral structure, effective skeletal/ muscular frame to enable more natural movement. ANTS structures will be used for exploration, communication, transportation, construction and for the protection of human crews.

The mission Lander Amorphous Rover Antenna (LARA) is in cooperation with the targets for the Moon and Mars. The aim of this mission is to provide robotic assistance to human crews on the Moon and Mars and to supply evidences of resources, biological precursors, and life.

LARA frame components are electromechanical structures forming a continuous network of struts. Nodes and Struts would be used for all functions .The movement across a terrain is so that the efficiency is optimized. Single tetrahedron (Figure 7.3) rocks from side to side as it moves forward. The tetrahedron is a polyhedron with properties which make it optimally suited for stability and space filling. Motion is continuous, more natural than wheels, allowing flow across a surface and into a particular morphological form. The prototype is being constructed from macroscopic electromechanical systems (EMS). As nano-EMS become available such components could be produced to minimize mass and power requirements, within the next decade or two. An outer covering of the LARA craft, could be produced by using designed nodes which apply carbon fiber composite memory sheets with low aerial density using Polymer/Carbon Nanotube Composite (PNC) springs and structural elements [Clark, 2004].

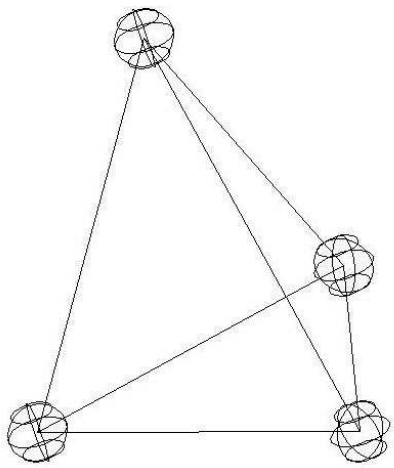


Figure 7.3: Single tetrahedron- illustration, Pelin Berik.

The goal is to minimize tetrahedral walkers to nano-size by using micro electro mechanical systems for the motors and carbon nanotubes for the struts. A large number of them will be joined together to form a swarm.

7.3 Nanorobots for Repair of Marssuit Damage

Surface exploration is the most important part of the Mars mission and it requires long periods of Mars surface activity. For some activities that robots can not achieve, humans must be sent to Mars surface. Manned Mars activities present considerable risk of damage to the Marssuit. The damage problem during Mars surface activity can be solved by the application of nanotechnology. When an astronaut is in the field, nanorobots can repair damaged suit materials (Figure 7.4) or prevent the urgent need to return immediately to a pressurized area.

Marssuit Repair Nanorobots (MRN) function as space-filling polyhedra to repair damage to a Marssuit. Assembler nanorobots produce MRNs, utilize chemical data storage, and they can also repair themselves.

A specially constructed tank in the habitat is the place for the assembly process. MRN nanorobots and assemblers are manufactured in this tank whenever needed. MRN nanorobots are removed from the solution, added to the suit to find the damage and then repair it [Chui, Kissner; 2000].

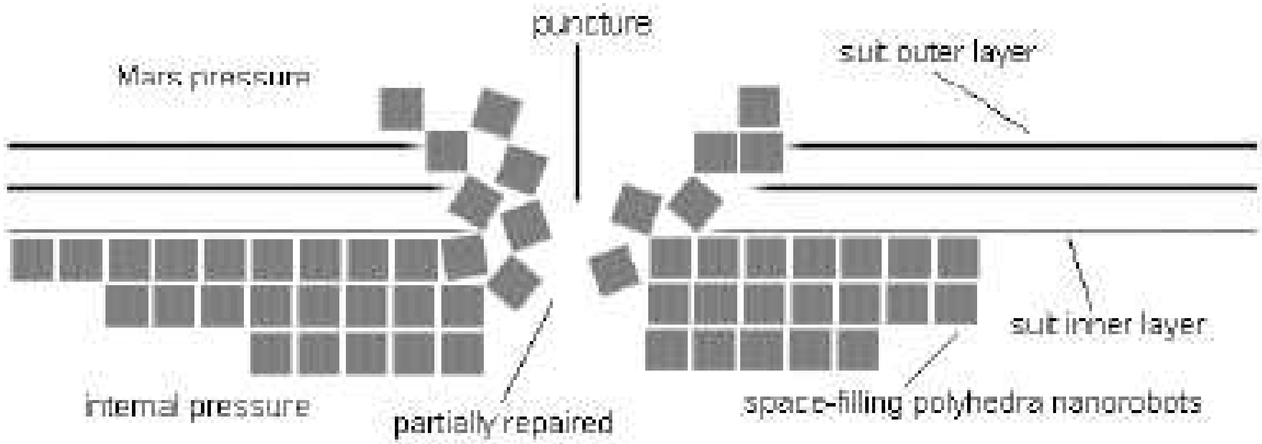


Figure 7.4: Space-Filling Polyhedral Nanorobots – They rapidly converge upon damaged areas and seal them-[Chui, Kissner; 2000].

If efficient control of atomic level constructions is achieved in the future, the construction robot must have hands that are equivalent in scale. A manipulator must have six degrees of freedom for an atomic construction. The Stewart platform (Figure 7.5) is a possible manipulator construction. It is parallel manipulator using an octahedral assembly of struts [Merkle, 1997].This platform is composed of a tool-holding mechanism with a triangular base and six movable struts, each of the them is 100 nm. The tip of the Stewart platform functions as a versatile nest site where variable molecular tools can be affixed for nanorobotic purposes [Stewart, 1965-66].

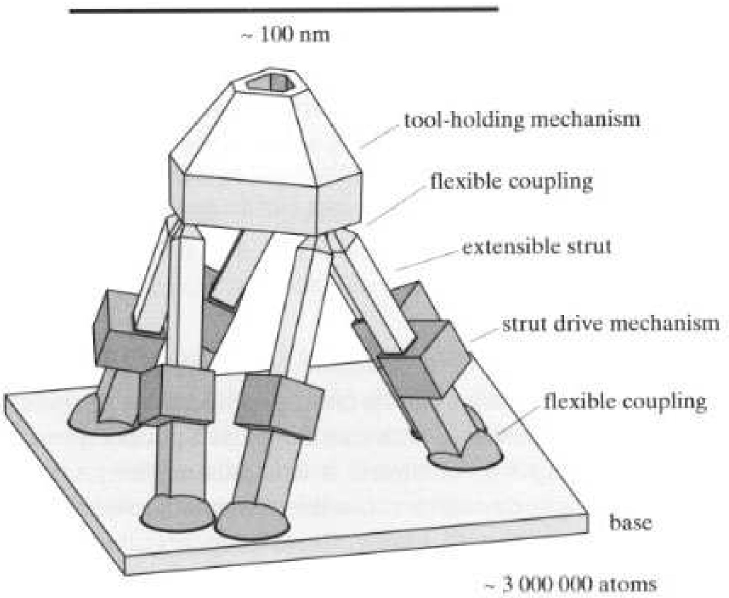


Figure 7.5: The Stewart Platform- illustrated by Drexler (1992).

The minimum strut diameter is 1.4 nm. For nanometer construction, SWNT nanotubes are ideal structural elements. Single wall carbon nanotubes can be precisely used as struts. SWNT nanotubes are the best molecular structure and supply all the properties that are needed. They can act as linear actuators (Figure 7.6) because of their hollow cylindrical nature and high modulus. Nanotube actuators can be driven by pressure differences. The nanotube strut can be made to extend or retract by varying the internal pressure.

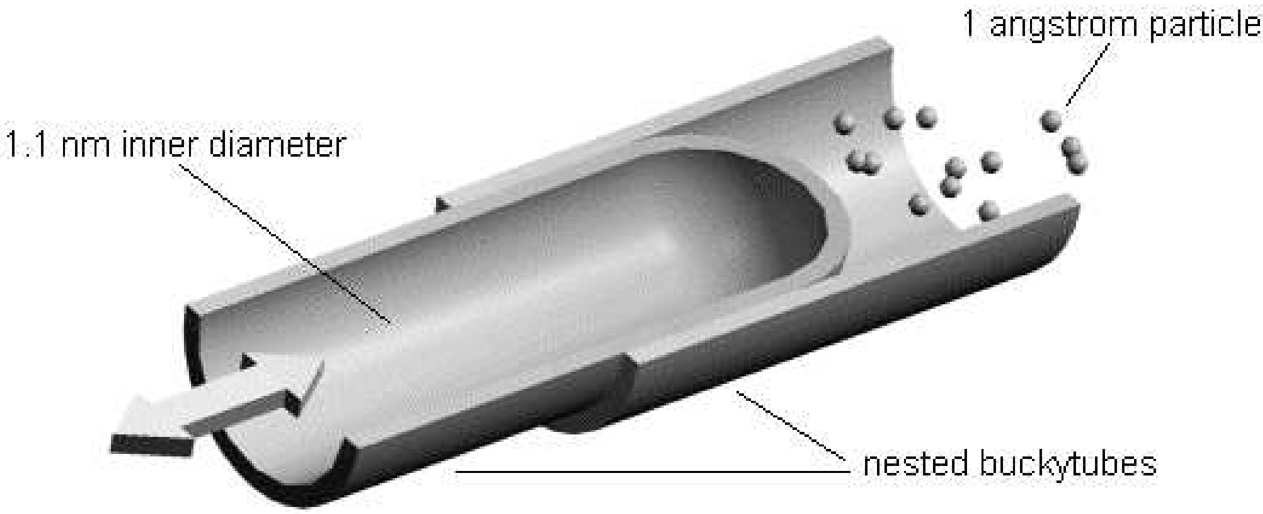


Figure 7.6: Molecular Actuator – A carbon nanotube can function as a molecular actuator-[Chui, Kissner; 2000].

The assembler can be regarded as a factory, each Stewart as a tool, MRN nanorobots as an active adhesive sealant. In the case of a breach, the robots tumble end-over-end in order to form a protective seal. Space-filling polyhedra are similar to biological platelets. There will be no waste time if an effective layer of these polyhedral nanorobots present in the Marssuit. The nanorobots layer upon one another until they have formed a barrier around the damage. The most important concern in case of suit damage is the gas leakage. Therefore the main function of MRN nanorobots is to seal the breach to prevent rapid gas loss. MRN nanorobots must be able to find their path to the suit damage, detect it, and adhere to the surface. They can be programmed to move like gas molecules in order to minimize sensor requirements.

Carbon nanotube materials will replace contemporary composites in aerospace applications. High tensile strength nanotube fabrics can prevent Marssuit punctures in all conditions. Marssuits will undoubtedly use this advanced material.

7.4 Space Bionanorobotic Systems

Space Bionanorobotic Systems are designed according to bio-nano-mechanisms formed by protein and DNA based nano-components. They will communicate and collaborate with each other in order to build, repair, and manipulate other objects in space. They can maintain their life and create other life.

Bio-nano components from biological systems are the first level of the progress of advanced bio-nano robots for future space applications. They can be simple members like structural links or advanced concepts like motors. Carbon nanotubes can be transformed into different shapes, and used for complex devices. They are the best nanostructures for the containment and the integration of the bio-nano components within them.

The Figure 7.7 shows a bio-nano robot from carbon nanotubes. Their feet are made of helical peptides. Carbon nano-tubes form the main body. The power unit is a biomolecular motor located at the head for the management of the device in different environments.

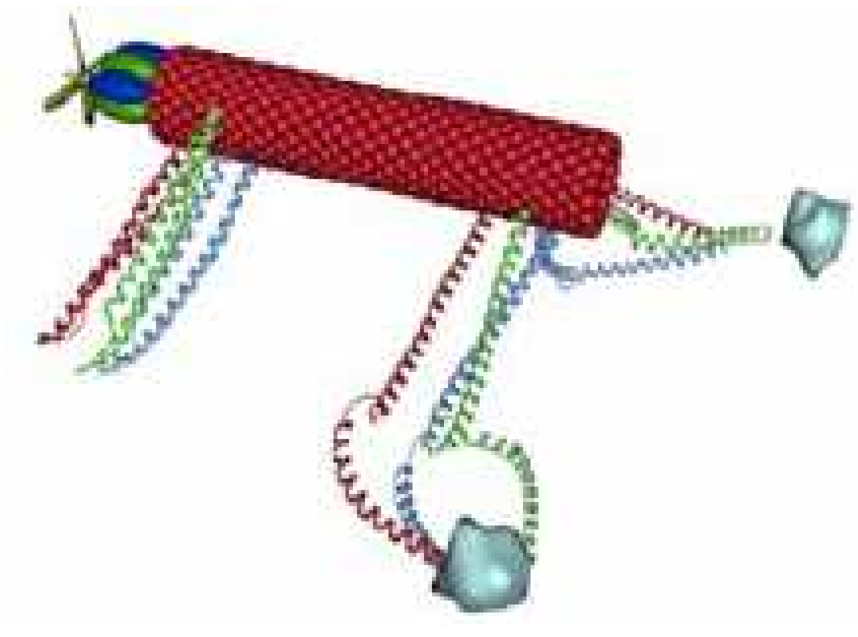


Figure 7.7: A bio-nano robot made of carbon nanotubes-[Mavroidis, Ummat; 2005].

Networked TerraXplorers

Networked TerraXplorers is a concept design for the application of bio-nano robotic systems. They are light weight, low cost and able to self-assemble and self – replicate. They land in large quantities on the target area (Figure 7.8) in the space to sense and map the terrain. It is a network of channels and contains the bio-nano robots. The bio-nano robots move inside the channels of the network, they interact with the terrain through special valves, and sense if the water exists or the minerals and other sources.

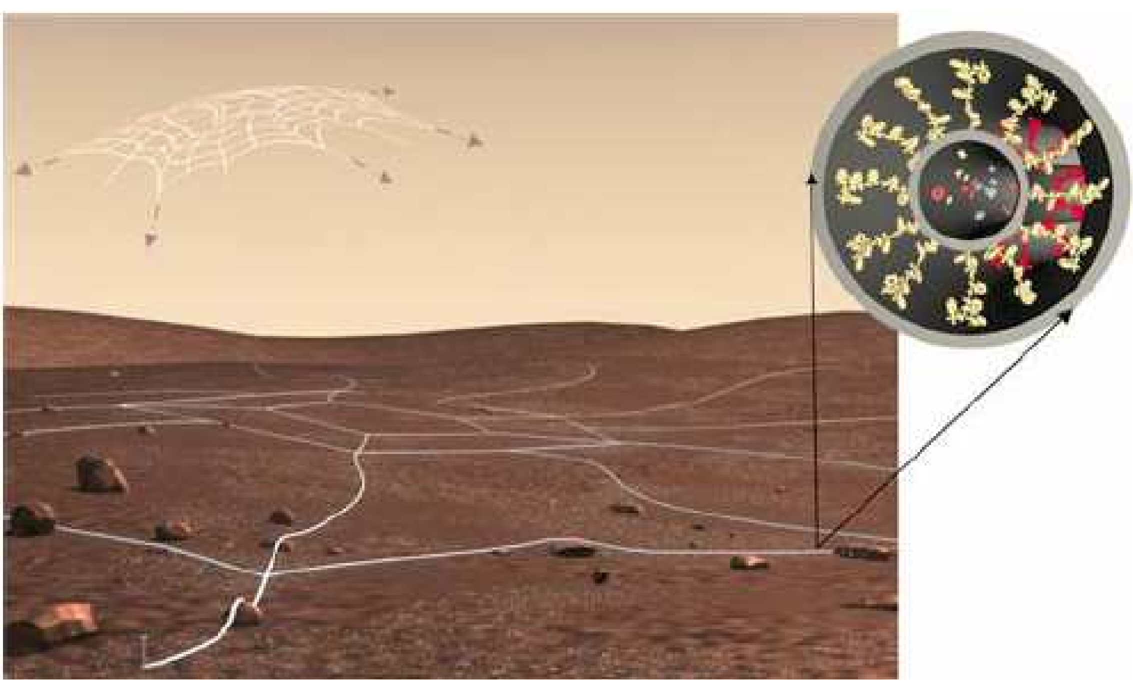


Figure 7.8: The Networked TerraXplorers (NTXp)- [Mavroidis, Ummat; 2005].

The black central node functions (Figure 7.9) as the central processor. It is responsible for the integration of the entire mesh and for the communication through inner layer. Central node also communicates with the orbiting satellite or other receiving stations. The biomodules required by the basic bio-nano robots are transported by the inner layer which carries signaling bio-nano robots. The outer layer senses the environment. It signals the findings back to the central unit.

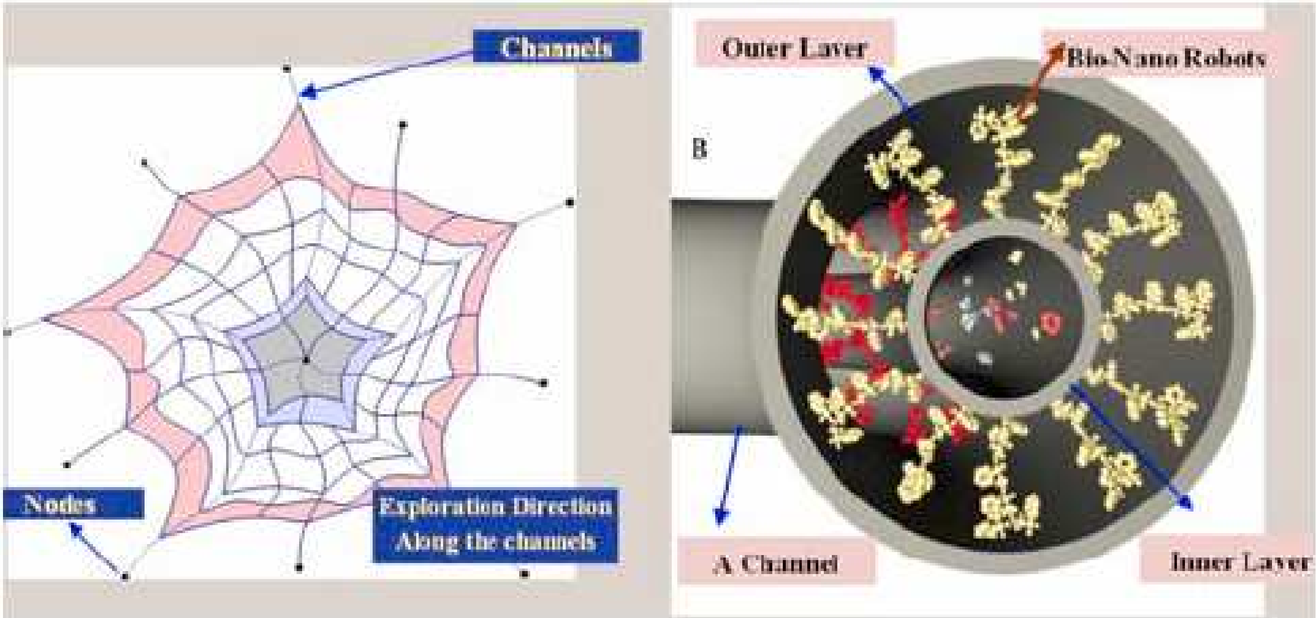


Figure 7.9: Central Processor and the cross-section of the Networked TerraXplorers-[Mavroidis, Ummat; 2005].

Networked TerraXplorers can guide rovers and human explorers for exploration of the terrain and showing them the direction they should follow. With the help of these networks, discovery of caves and low lying surfaces can be achieved. Because of harsh conditions on the planetary surface like radiations, temperature, pressure, the micro channels will be designed in various layers which have specific functions and contain specifically designed bio-nano robots. The outer skin of the network can be polyethylene polymer and protect the bio-nano robots from the harmful radioactive radiations.

NTXps can be designed in macro level and Micro level. Macro level can be miles long and integrated to a unitary central unit, and the micro level can be only few millimeters. This Micro NTXp can be sprayed from the air borne rover or orbiter to the desired location. These micro networks can be easily flown by the winds and currents and give information about the details of the structure of the storms and winds on the planet.

The All Terrain Bio-nano Gears (ATB)

A multifunction system which functions as early warning and protection system against chemicals, radiations, temperature and pressure for the astronauts is needed to ensure health security of astronauts on future space missions. This system will be like an adaptive shield protecting from possible health hazards and form a complementary layer beneath the current or any other future space suits. An ATB gear (Figure 7.10) functions as described and has mentioned capabilities. It is lightweight, flexible and allows the astronauts to wear it all the time.

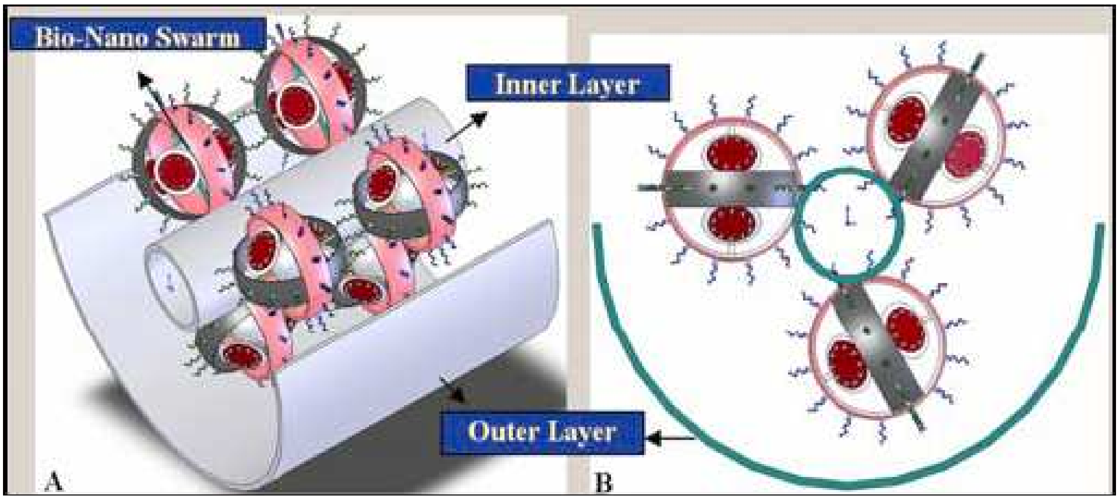


Figure 7.10: The ATB gear-[Mavroidis, Ummat; 2005].

The bio-nano swarms are arranged in many channels and form the ATB gear. The swarms penetrate the inner layer of the channel to sense and signal. These swarms have multiple layers with various layers and functionalities. ATB gears can form a self-healing layer for the astronaut's space suit. Different layers of the ATB gear (Figure 7.11) are interwoven with the inner layer of the space suit. The bio-nano robots inside these ATB gears move to the site and seal it if some breach is detected .This feature gives the terrain mobile astronauts enough time to find a shelter or other solution. The ATB gears are considered as an integral part of the space suits in order to protect and warn the astronaut against any possible health hazard.

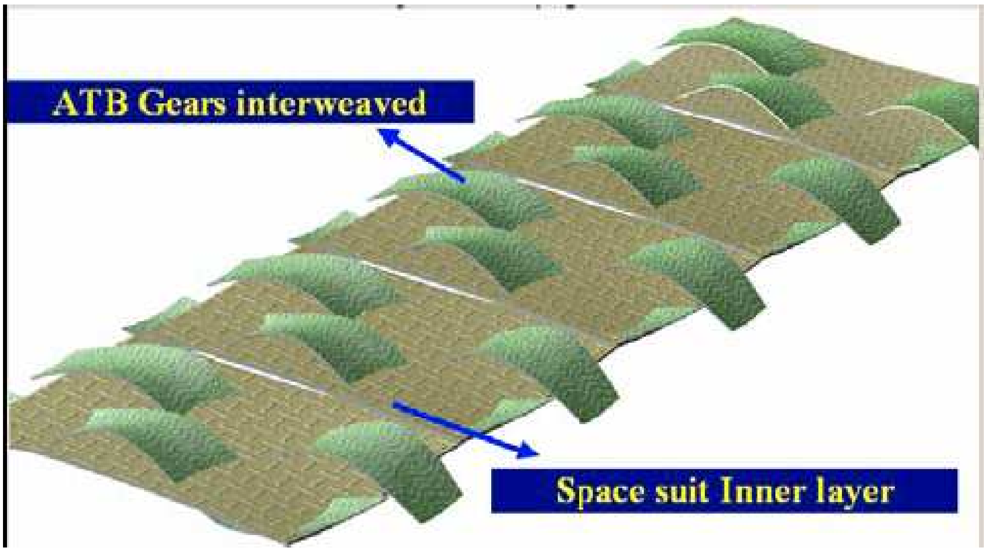


Figure 7.11: Interwoven ATB gears-[Mavroidis, Ummat; 2005].

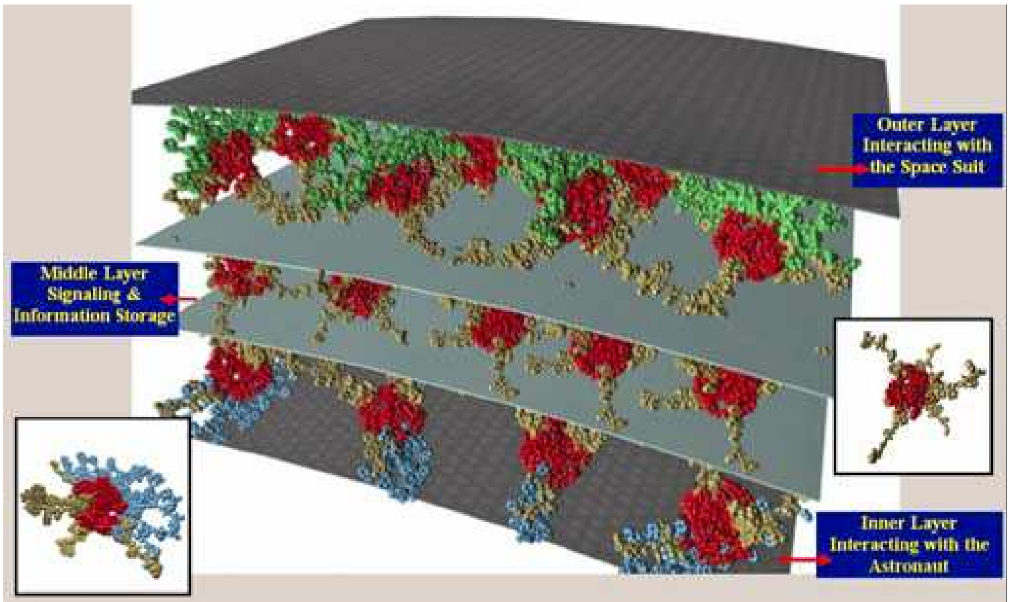


Figure 7.12: The layered concept-[Mavroidis, Ummat; 2005].

The inner layer contacts with the human body (Figure 7.12). The outer layer senses the outer environment. The middle layer is responsible for communicating, signaling and drug delivery. These bio-nano robots cover the skin of the astronaut to decrease the intensity of the wound if an injury exists. They can also transport the wound healing drugs. Healing drugs are stored in the bio-nano robots. The bio nano robots can accelerate the flow of excess robots. Excess robots are stored in a stock on board the astronaut suit and the protection with their signaling capabilities. They can also sense the temperature variations in the astronaut's body and signal unexpected events.

Although the harmful radiation protection layer on the outside layer protect the astronauts from harmful radiations, if the radiations penetrate through the outer layer, the bio robots alert the astronaut to seek a more protective place. They can protect and heal. Until the astronaut finds a secure place, bio robots cover the breach by the movement of protective agents (Figure 7.13). The drug molecules are injected into the infected area and accelerate the recovery for the astronaut [Mavroidis, Ummat; 2005].

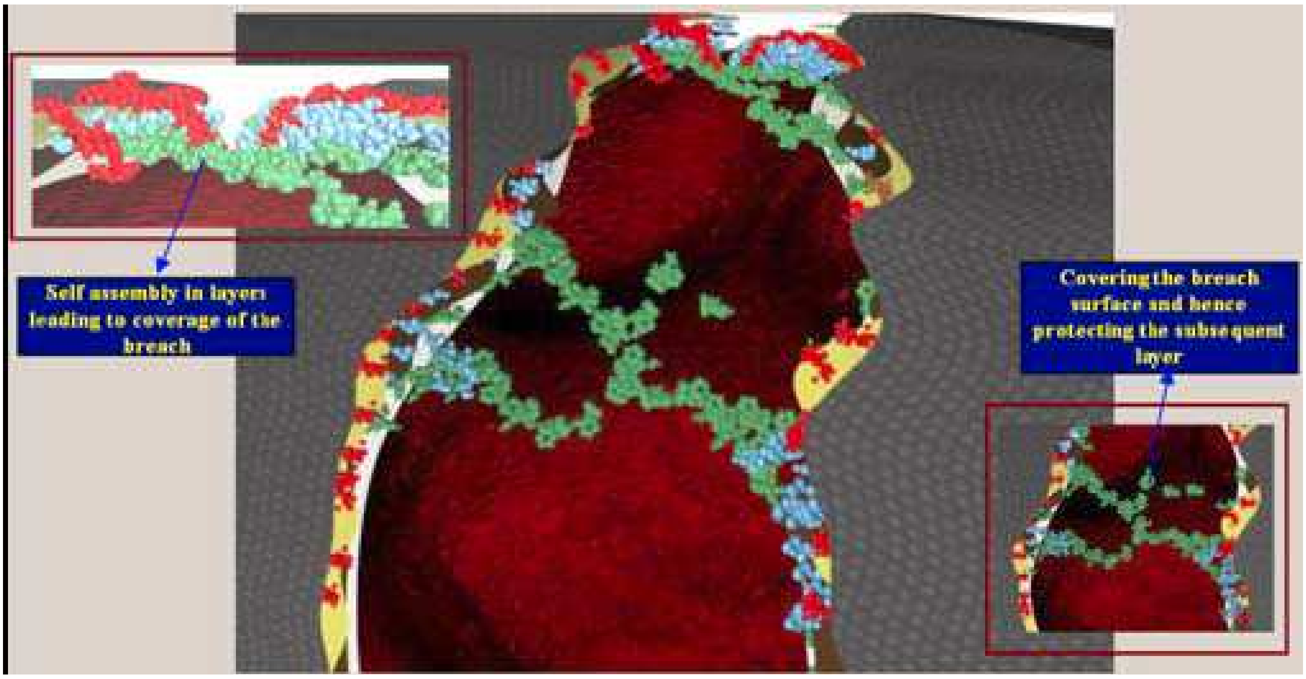


Figure 7.13: Curing a wound by the ATB gear-[Mavroidis, Ummat; 2005].

8. Solar Cells and Nanotechnology

Solar cell converts sunlight into electricity. They are a class of semiconductors, and based on the photovoltaic effect to absorb the energy of the sun and cause current to flow between two oppositely charge layers.

They absorb energy through photons, when light comes to the cells. This absorbed energy cause electrons in the silicon to flow. An electric field can be obtained with the addition of different impurities to the silicon like phosphorus or boron. This electric field allows electrons to flow only in one direction, because of that acts as a diode. As result a current is obtained (Figure 8.1). A solar cell's energy conversion efficiency is the percentage of power converted and collected, when a solar cell is connected to an electrical circuit. The efficiency can be increased significantly by application of nanomaterials. Solar cell from III/V-semiconductors such as GaAs and InP are the most efficient solar cells for space applications at the present.

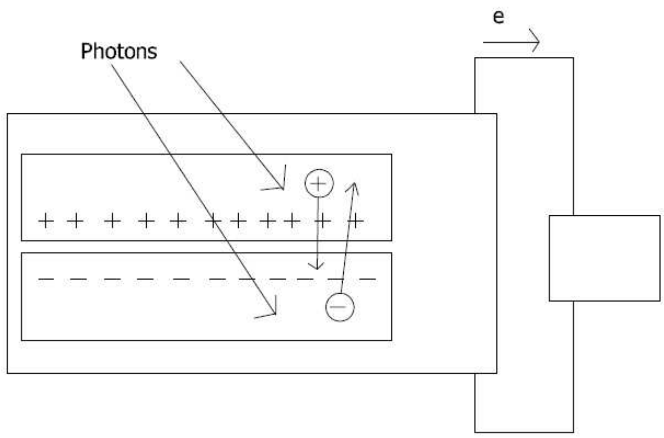


Figure 8.1: Photovoltaic solar cell-Schematic by Pelin Berik.

Space photovoltaic arrays have been in space since 1957. Silicon cells were used as the power source for the initial flight on the Vanguard satellite. Single crystal CdS with a Cu_2S active layer were other options. They were 1x1 cm in size. But, the silicon solar cell was preferred in space, because of the use of silicon in the electronics industry. Space missions away from the sun did not use a photovoltaic power system and they were powered by a nuclear reactor.

With the application of nanotechnology new designs for low cost solar cells can emerge. New solar cells can be made from made from nanoparticles, nanotubes. Nanomaterials enable more efficient use of solar energy and lower costs.

8.1 Space Environment for Solar Cells

Low Earth Orbit (LEO), Geosynchronous Earth Orbit (GEO) and mid-Earth Orbit (MEO) are three general earth orbital conditions. The most of the satellites exist in LEO and GEO. In LEO limited space radiation exists but there are micrometeoroids and atomic oxygen. For earth observation and space stations, these orbits are used. GEO has no atomic oxygen but electron, proton space radiation and solar flares. GEO satellites are affected by space charging. Space charging causes serious arcing and loss of the power system. Because of that this orbit is used for global weather and communications satellites.

For missions at Mercury, the solar intensity is about 9400 W/m^2.Solar array temperatures can reach over 200 ºC, for this reason special designs must be considered. Because of its high temperature and opaque atmosphere, solar arrays can not be used on the surface of Venus.

Mars is suitable for the application of solar arrays. The Mars Exploration Rovers Spirit and Opportunity have been operated well with horizontal solar arrays. At Jupiter the use of solar arrays is limited. The distance from the Sun (5.2 A.U.) and the intense radiation belts are the causes of this limitation. However, solar-powered missions can be possible, with the modern lightweight, radiation-tolerant array designs. The solar intensity is too low for solar arrays considerations for satellite power supplies beyond Jupiter [Brandhorst, 2003].

8.2 Solar Cell Options

The classes of present space solar cells: silicon cells, multi-junction crystalline cells, thin film cells and emerging cells such as quantum dot cells.

Silicon cells were the foundation for further theoretical understanding and new designs. The first silicon cells were about 7% efficient. The efficiency increased to over 17% in the next 20 years. The use of them comes no longer into consideration. Few satellites still prefer these cells. But, In the US they are not produced more.

GaAs-based III-V Solar Cells occurred in 1982. An 18% efficient 2x2 cm GaAs cell made by liquid phase epitaxy was developed. Then the cells were by vapor phase epitaxy. The costly GaAs substrate was soon replaced by Ge. This cell is in use today. The use of vapor phase epitaxy was a step for the development of the multi-junction cells of today. The efficiencies of these solar cells are approximately 30% and 33% and will be 40 % in the next decade.

CdS/Cu_2S thin film solar cells occurred at the beginning of the 1960s.Because of its low efficiency, namely ca. 5-7 %, the use of thin film cells is limited. It was resistant to electron and proton radiation and the damage can be annealed. But, process control and cell uniformity in production were problematical. In space cycle tests in vacuum problems also occurred. The amorphous silicon cell (Si/SiGe/SiGe cell) took attention 30 years before. But, because of low the efficiency, 10%, its future use in space is not possible.

The most available thin film cell is the copper indium-gallium di-selenide (CIGS) cell, with an efficiency of 10-12%. It is resistant to radiation damage and the damage can be annealed. But, the low efficiency is again a limiting factor and it has not the uniformity needed for space use. Further manufacturing control is also required to match thin film cells into an array.

Nano-composite, quantum well cells, quantum dot cells, dye cells and organic cells are new emerging solar cells. More efficient space solar cells can result in improved satellites and solar energy technology. Using nanotechnology can increase this possibility.

The application of nanoscale crystals, quantum dots, can change the way a solar cell absorbs light and converts it into electricity. The electrical, optical, mechanical and even thermal properties of nanomaterials can be controlled by changing the particle size. This makes them useful in semiconductor device development.

Other types of cells are the organic and dye-based cells are not resistant to space environment.

8.3 Nanocrystal Solar Cells (Quantum dot solar cells)

Nanocrystal solar cells are based on nanocrystals. They are still on the research level. With quantum dot-modified solar cells energy conversion efficiency can be achieve up to 50 percent, because of multiple exciton generation.

The advantages for nanostructured solar cells include beside their high efficiency by multiple exciton generation, overcoming of limitations related to lattice matching and low fabrication costs.

Current solar-cell technology for space power is based on mainly three individual photovoltaic junctions used in a series. Triple-junction solar cells consist of the chemical compounds, germanium, gallium arsenide and indium gallium phosphide. They are grown latticed-matched on top of one another. The efficiency of the triple junction cell and cell short-circuit current can be improved by the incorporation of the middle cell in the three-layered sandwich with a quantum dot array (Figure 8.2) [Raffaelle, 2002].

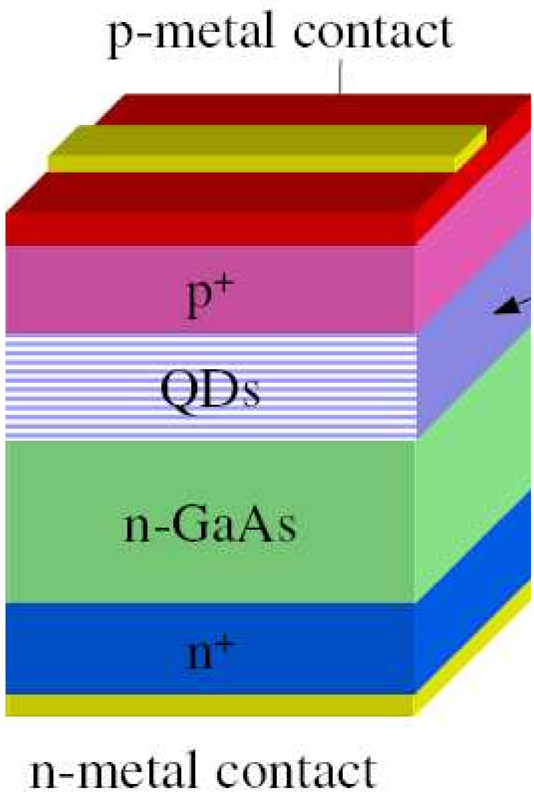


Figure 8.2: The incorporation of quantum dot.

When an atom is hit by a photon, it leaves a hole, referred to as an exciton. An exciton is an electron–hole pair created by a photon. A quantum dot is able to emit multiple excitons. Many excitons must occur until enough energy produced. But quantum dots can produce multiple excitons (Figure 8.3). This means more solar power [Pearsall, 2000].

In quantum dots, the band gaps can be changed specifically to convert also longer-wave light .This increases the efficiency of the solar cells. For quantum dot solar cells III/V-semiconductors and other material combinations such as Si/Ge or Si/Be, Te/Se are considered as production materials.

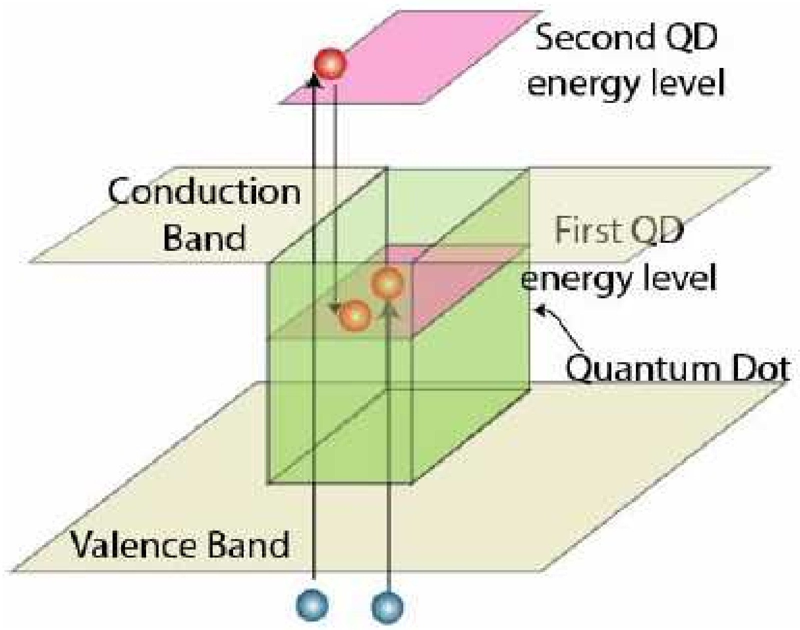


Figure 8.3: Multiple Exciton Generation- [Honsberg, 2006].

Each nanocrystalline dot acts as a potential source with energy levels. These energy levels are quantized and inversely related to the size of the well. The absorption energy of the dot can be made complementary to the existing cell properties, by modifying the size of the particle.

In another approach is the attachment of quantum dots to single wall nano-tubes (Figure 8.4). This attachment creates a host. The host is conductive and allows multiple size dots to be attached. It can increase the efficiency.

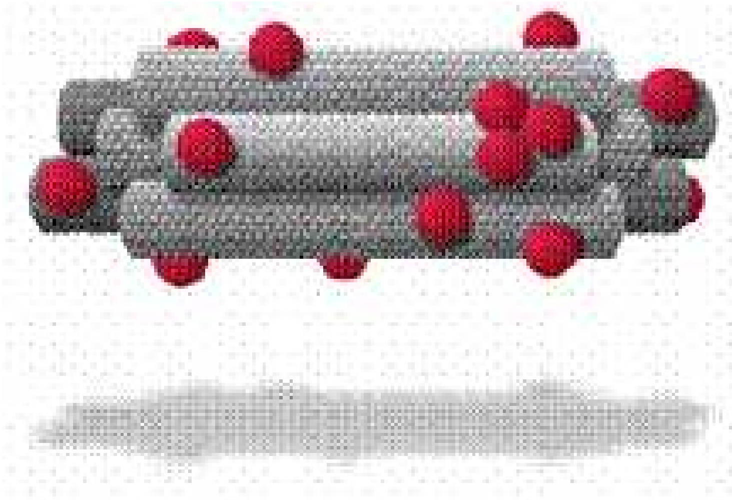


Figure 8.4: QD-SWNT complex-[Brandhorst, 2003].

Another alternative material for solar cells based on nanotechnolgy is conjugated polymer-SWNTs composite. This material can be used to manufacture organic photovoltaic cells and to increase the performance (Figure 8.5). In this approach P3OT is incorporated with single walled carbon nanotubes and acts as the photoexcited electron donors. Carbon nanotubes act as the electron acceptors. The interaction of the carbon nanotubes with the polymer leads to charge separation of the photogenerated excitons in the polymer and efficient electron transport to the electrode through the nanotubes. The SWNTs increases the electron mobility through the solar cell and improve the photovoltaic performance [Kymakis, 2002].

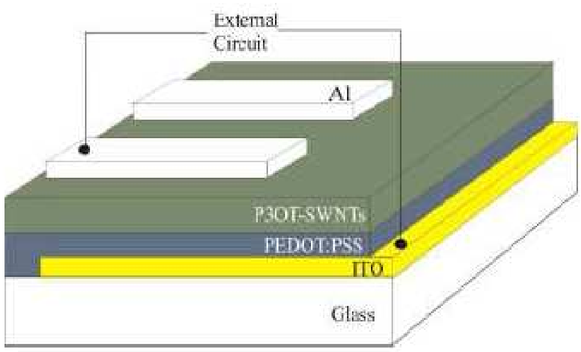


Figure 8.5: Conjugated polymer-nanotube solar cells-Schematic-[Kymakis, 2002].

Another carbon nanotube solar cell design is to produce carbon nanotube towers atop photovoltaic cells to extract more power from the sun. This nanometer-scale scale towers (Figure 8.6) increase the surface area available to produce electricity. They give more opportunity for each photon of sunlight to interact with the p/n junction of the cell. The power output from PV cells of a given size would be increased. The cells could be smaller, but they would still produce the same output. Block towers of aligned carbon nanotubes grow on iron catalyst at 700°C by chemical vapor deposition synthesis [Ready, 2006]. These three-dimensional cells can be also used in space applications.

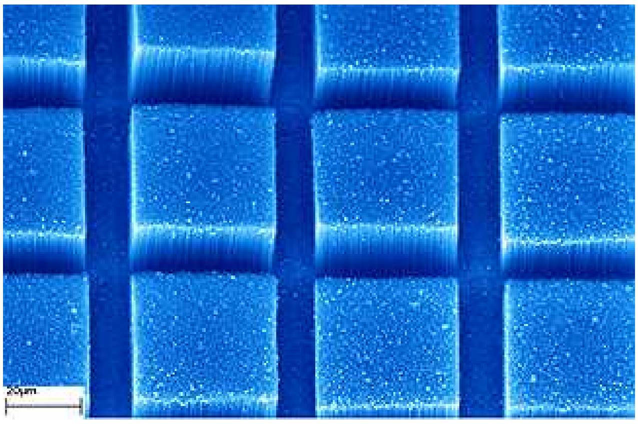


Figure 8.6: aligned carbon nanotubes towers-[Ready, 2006].

8.4 Solar arrays on Mars

The environmental conditions on the surface of Mars are quite different from the Earth's surface or orbital environment. These different conditions such as lower solar density, atmospheric dust, low temperatures, and deposition of dust on the arrays affect the performance of the solar cells in the array [Appelbaum, Landis, Sherman, 1993]. Dusty atmosphere changes the solar spectrum and reduces intensity [Landis, Jenkins; 2000]. Therefore, photovoltaic arrays on the surface of Mars present special requirements. The performance of a solar array is the focus point for many proposed Mars missions.

The atmosphere of Mars shields the 20 gram/cm2 of the radiation. Because of that radiation is not an important cause of degradation at Mars surface. The redder spectrum of Mars and the low operating temperature lower solar cell efficiencies. For roving vehicles small vehicles are needed and array area is very limited. This requirement is another accelerator for high-efficiency solar cell designs. For example, for the two Mars Exploration Rovers (Figure 8.7), which landed on Mars in January 2004, GaInP/GaAs/Ge triple-junction cells were selected.

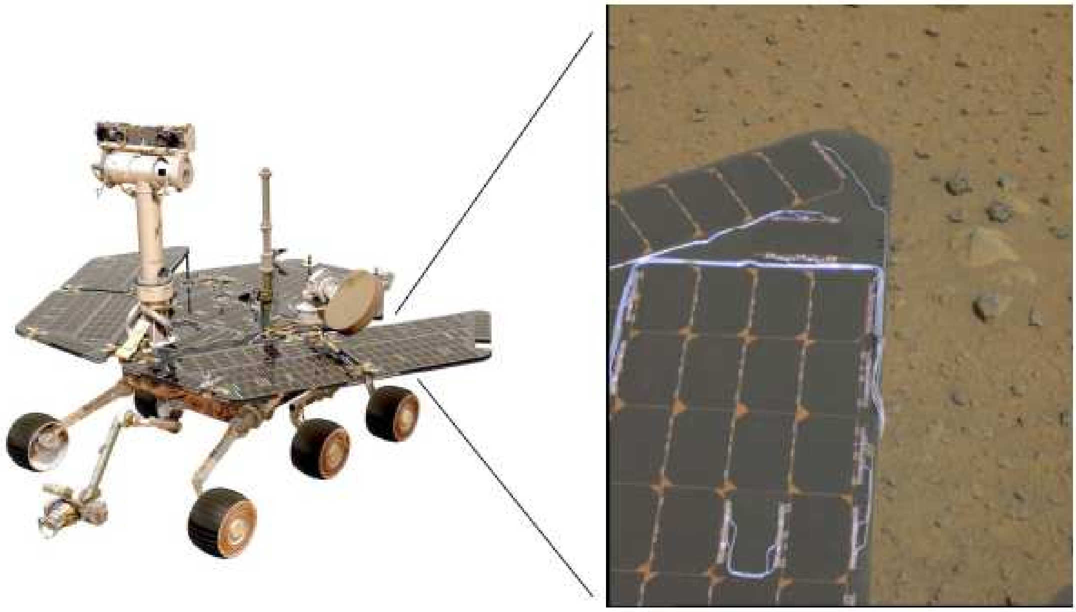


Figure 8.7: Mars Exploration Rover on Mars and its solar array- NASA.

Another environmental affecting conditions for array materials are wind loading, peroxide components of the soil, low atmospheric pressure, electrostatic charging [Sentman, 1991] and possible Paschen discharge [Leach, 1991].

Polar lander missions are studies to track Mars climate history and exobiology. Landers are limited to a single locality to conduct scientific operations. But, a rover searches for an extended area and selects interesting surface features. For this missions triple-junction GaInP2/GaAs/Ge photovoltaic cells were selected to minimize array area and mass and maximize the efficiency. A vertical array can reduce the dust deposits on surfaces (Figure 8.9).

Figure 8.9: Vertical solar array- The Long Day's Drive Rover,
a Proposed Scout Mission.

Solar arrays can be also applied for human missions to Mars. As the primary power source for In-situ resource utilization plant, a large solar array can be used. This plant converts the carbon dioxide atmosphere of Mars into rocket propellant. This design applies the tent array structure (Figure 8.10). A similar design is also proposed for lunar base PV applications [Landis, 1990]. The advantages of this design include structural efficiency, east-west tent orientation giving more power in morning and afternoon and less dust deposition. Dust does not adhere to tilted surface [Landis, 2004].

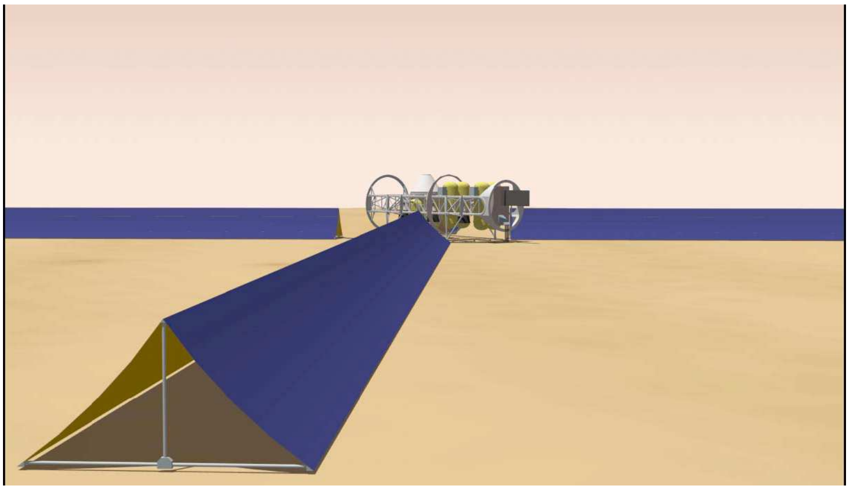


Figure 8.10: Mars Solar Array for a Plant to Manufacture Propellant for a Human Mission, using four tent solar arrays- NASA.

9. Nanosatellites

Nanosatellites have a total mass of 10 kg or less, including propulsion systems. Nanotechnology can revolutionize the satellite design. Nanotechnology can reduce devices in size, weight, and power requirements. Nanodevices operate at the molecular or even atomic scale. But, nanotechnology is still under development, and it can take many years until real nanodevices are available in space. Some examples of nanodevices are molecular computers, nanomechanical computers, quantum computers, single-electron transistors, quantum dot cells, conducting molecular wires, self-assembling circuit arrays, nanomanipulators. The average size of satellites continues to decrease. Satellite cost is proportional to its mass. This means the lower the total spacecraft mass, the lower the cost.

Nanosatellites enable the development from single expensive platforms to smaller, low-cost platforms. Because of their limited capabilities, nanosatellites are generally not practical in small numbers. The dimension limit of a small spacecraft is dependent on the dimensions of small electromechanical actuators. These actuators are called generally as microelectromechanical systems (MEMS). They are researched intensively and still under development.

Designing a nanosatellite is to apply design techniques to create a scaled-down version of a traditional satellite, and miniature components are used. Over 20 nanosatellites are in the use in space. The application of nanosatellite swarms and constellations are in consideration. The aim of nanosatelllite swarms includes execution of measurements for earth observation or planetary exploration and sensor networks for 3-D photographs.

Nanotechnology can give solutions by providing MEMS-propulsion technologies, lightweight materials, miniaturized cooling loops and heat exchangers, solar cells and sensors.

Microtechnology means the application of micromachines, micro electromechanical systems, micro opto-electromechanical systems, and other micromachined devices. They give size, weight, and power reductions. Some of spacecraft microtechnology applications are showed in the table 3. But, there are few available devices for space applications. Miniaturized sensors like magnetometers or accelerometers are mostly used applications [Jackson, Epstein; 2000].

Subsystem	**Microtechnology Application**
Structure	Adaptive damping structures, microlaminate structures
Mechanisms	Micro mirror actuators, millimachined actuators
Thermal Control	Micro louvers
Propulsion	Micro-nozzle array
Electrical Power	Micro turbine Micro switches
Attitude Determination	Micro magnetometer, accelerometer, gyros
Communications	Micro filters, delay lines, configurable array antennas
Cmd & Data Handling	Micromechanical computer

Table 3: Spacecraft microtechnology applications- [Jackson, Epstein; 2000].

Nanostructured diamond-like carbon layers possess four times a higher thermal conductivity than copper. Because of that, they can improve thermal control systems of nanosatellites [Rossoni, 1999]. Nanomaterials improve thermal control of space travel systems.

Ferrofluids are magnetic nanoparticles with the size of 5 to 50 nm in liquid. The pressure, the viscosity, the electrical and thermal conductivity of ferrofluids can be controlled by external magnetic fields. Because of that, they are considered for new designs [Wiltzius, Klabunde, 1999]. The magnetic manipulation of ferrofluids can give solutions for thermal conductivity control. Ferrofluids make possible magnetically precision temperature control of miniaturized electronic components.

The physical processes between the Sun and Earth require measurements from many points in space. Nanosatellite swarms can enable these required measurements. NASA's conceptual STP (Solar Terrestrial Probe Line) Constellation mission is an investigation project for in-situ measurements by the application of nanosatellites. One hundred nanosatellites will be employed to execute in-situ and remote measurements of magnetosphere in 2008 for two year mission life. This spacecraft (Figure 9.1) is cylindrical with a 30 cm diameter and a height of 10 cm.

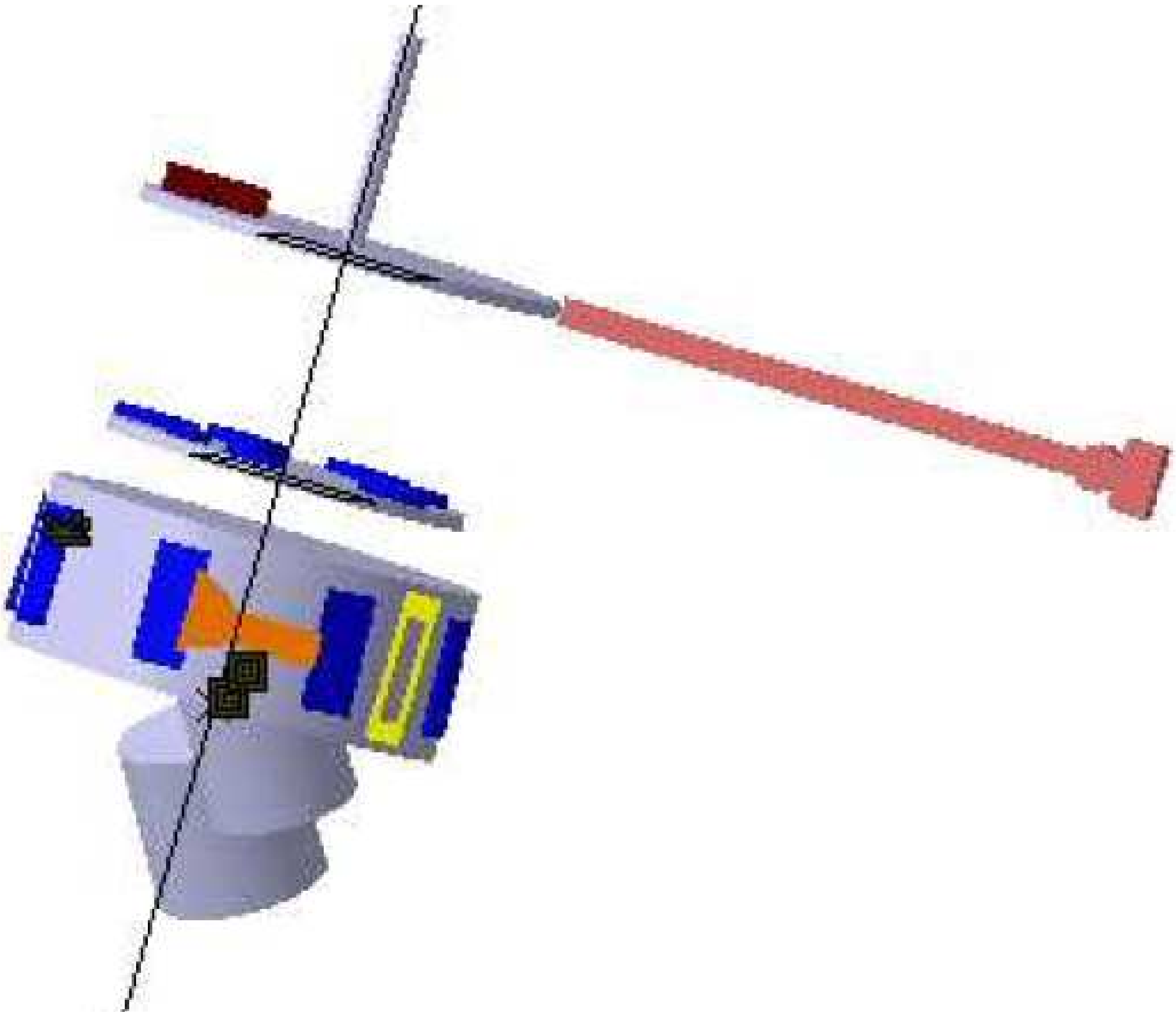


Figure 9.1: STP nanosatellite design- re-illustration by Pelin Berik.

Nanosatellite's spin-stabilized configuration with its spin axis normal to the ecliptic plane maximizes sunlight exposure on its solar cells. Solar cells are mounted on the circumference of the cylinder. The nanosatellite will be equipped with miniature instruments, measuring particles and fields. The nanosatellite mechanical system must be simple and consist of a one-piece structure and other components can be added to this structure. A deployer-ship (Figure 9.2) carries the nanosatellites into their orbits. It will be conventional spin-stabilized or three-axis stabilized spacecraft. Its spin axis is oriented in the desired location in order to release the nanosatellite. The important miniaturization techniques for nanostallites include miniaturized propulsion systems, sensors, electronics, heat transport systems, tracking systems for orbit determination, autonomy, lightweight batteries, high efficiency solar arrays, and advanced structural materials [Panetta, 2000].

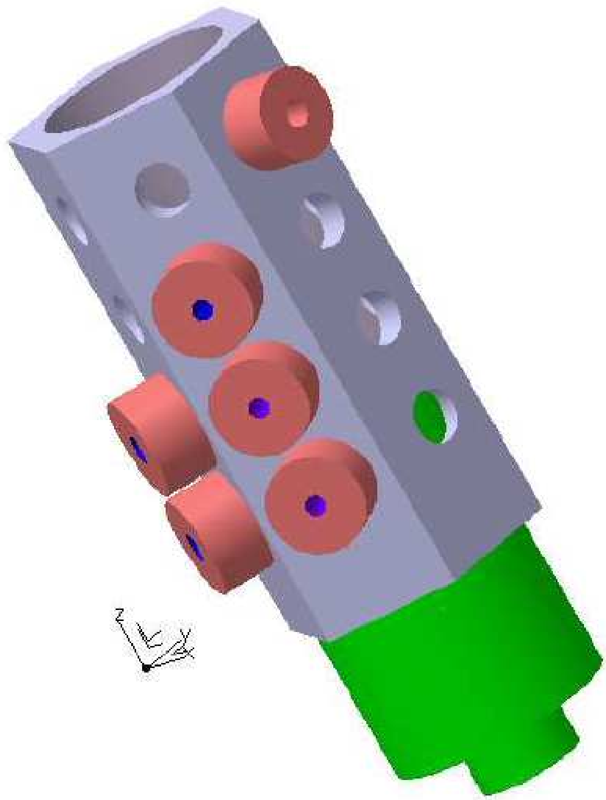


Figure 9.2: Deployer-ship design for nanosatellites- re-illustration by Pelin Berik.

10. Concluding Remarks

Nanotechnology enables human and robotic exploration of space. Space travel and on long-duration missions are actually hazardous, nanotechnology can minimize the risk of space missions. Nanocomposite materials such as nanostructured ceramics, fiber composites, nanoparticle reinforced polymers offer high-strength, lightweight space structures, lower production costs, and protect spacecrafts against the harsh conditions of space as thermal protection systems. Carbon nanotube is one of the most significant inventions of nanotechnology for space applications with its high-strength, flexible and special properties. Nanorobots can execute dangerous jobs in space and also protect astronauts in case of damage of their spacesuits. Nanotechnology makes the realization of visionary concept designs like space elevator and solar sails possible. Planetary surfaces can be investigated by the use of atomic force microscopes. The compounds of III/V column elements provide the most possible efficient solar cells at the present. Nanotechnology can be the basis for design and construction of more advanced space structures.

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