Systems Analysis of Carbon Nanotubes: Opportunities and Challenges for Space Applications

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Abstract

Recent availability of carbon nanotubes in quantities and formats amenable to producing macroscale components invites consideration of these materials in space applications where their attractive properties can enable the realization of bold concepts for affordable space exploration. The challenge is to identify relevant systems and quantify the benefits at the systems level. Before significant investment or adoption of carbon nanotubes for large aerospace systems can be justified, there must be a reasonable path to attain the perceived systems level benefits. This challenging step requires a close collaboration among experts on carbon nanotubes and aerospace system communities. This paper provides an overview of a few relevant potential carbon nanotubes applications for space systems and the gap that must be overcome for deployment of CNTs. It also provides a simple engineering-level systems analysis approach to quantify the benefits of using CNTs over state of the art material solutions.

Introduction

Carbon nanotubes (CNTs) have garnered significant global attention since the seminal work published (Iijima, 1991). Early reports on their inherent multifunctionality generated great interest in game changing possibilities for aerospace applications. It was anticipated that challenging problems hindering affordable space exploration can be overcome by taking advantage of various properties of CNTs that are superior to state of the art (SOA) materials currently being employed. Among the early adopters for this emerging technology is NASA's Juno mission, where CNTs were employed for electrostatic discharge dissipation (Houston, 2016). While many more applications have been cited for this versatile material, its insertion into real missions is still limited (De Volder et al., 2013). Only recent advancements in large-scale manufacturing of this material has permitted a broader assessment of their utility in aerospace applications (Gurau, 2014; Alvarez et al., 2015; Kim et al., 2016; DexMat Carbon, 2017; Space Technology, 2016). Focused development of this material can be aided by the prioritization of its utility in various mission scenarios that require the development of advanced materials to come to fruition. Future missions will seriously consider CNTs applications if they: 1) provide a significant mass advantage to offset their low technology readiness level (TRL), 2) enable unique capabilities that contribute substantial improvements toward mission success, and/or 3) improve the mission to the degree that a new paradigm for overall mission architecture can be considered.

One of the biggest challenges for CNT inclusion in a mission is the weak link between technology push—identified in reviews and roadmaps discussed in this paper—and actual mission demand (technology pull). The purpose of this work is twofold: 1) provide methods to quantify the system-level benefits of carbon nanotubes (CNTs) for missions and components of space architecture, and 2) identify CNT applications that would further amplify the benefits of CNTs. The discussions will be limited to space applications. A brief overview of existing surveys and roadmaps on CNTs is presented, followed by a description of space mission campaigns, system analysis, and opportunities and challenges for CNT applications.

CNT Reviews and Roadmaps

NASA has identified Nanotechnology as a promising new technology that will help NASA to achieve its extraordinary missions. An early report by Harris et al. (2002) presented a review that highlighted the potential applications of carbon nanotubes (CNT) for NASA missions. They show that polymer matrix and aluminum matrix composites reinforced with single-wall carbon nanotube (SWNT) offer orders of magnitude improvement over aluminum 2219-T87. The results were based on 0% minimum gauges and theoretical properties of the carbon nanotube fiber reinforced polymer using standard micromechanics equations. These conclusions assumed retention of nanoscale properties at the macroscale. They did not account for large volume manufacturing constraints and structural design considerations such as minimum gauge, supporting structures, durability, and application to non-load bearing components. For example, in the original system analysis study Talay et al. (2000) assumed that CNTs behaved like carbon fiber composites so strength properties were cut off at the 1% level of strain observed in current composite polymer systems; full nanotube strengths are only achievable at strains an order of magnitude greater than current composite strain allowable. The assumption may not acceptable for some design situations.

Meyyappan and Dastoor (2004) organized a workshop for nanotechnology in space exploration. One of the promising concepts identified in this workshop was thermal, radiation and impact protective shields (TRIPS), which are a multifunctional thermal protection system (TPS) concept. The base material is phenolic impregnated carbon ablators (PICA) that incorporate hydrogenated CNT, adding radiation shielding as a second functionality. The TRIPS concept uses small amounts of CNT that can store hydrogen. The storage level may not be adequate to make a significant difference (Go/No-Go Decision, 2006). The third functionality is a built-in micrometeorite and orbital debris (MMOD) protection. TRIPS is a single shield that can improve mission safety and performance against three threats. The TRIPS concept is an interesting example of technology push, which will be a challenge to include in future NASA missions without a technology pull that can identify and quantify the systems level benefits and risks (Meyyappan & Dastoor, 2004).

De Volder et al. (De Volder, 2013) provide a taxonomy of CNT commercial applications for the present and future. They raise important questions on lack of understanding as to why the properties of CNT yarns and sheets like thermal conductivity and mechanical strength; remain far lower than the properties of individual CNTs. It is important to retain the observed nanoscale properties at the macroscale if these materials are to find broad utility. This has remained a challenge, although progress is being made in understanding some of the factors that influence mechanical properties. In spite of this lack of understanding, commercial companies are investing in diverse applications of CNTs, many of which may have less stringent requirements than space applications where mass reduction; reliability and environmental durability are of prime importance.

The recent NASA Nanotechnology roadmap (Meador et al., 2015) includes a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmap focuses on “applied research” and “development” activities that have the greatest potential influence on NASA missions. The technology roadmap is broken into four major areas: 1) engineered materials and structures, 2) energy storage, power generation and power distribution, 3) propulsion, and 4) sensors, electronics, and devices.

While the widely reported properties of CNTs have inspired visions of game changing aerospace applications, there is often a weak link between speculated utility and actual mission demand, largely due to a lack of understanding of performance requirements and insertion opportunities for missions. Furthermore, early reviews identifying aerospace applications for CNTs were largely based on assumed retention of the nanoscale properties of these materials. With recent advancements in manufacturing scale-up for this material, the current state of CNT maturation permits a more realistic assessment of the application of CNTs for specific functions. Requirements for some applications are more attainable than others. In conjunction with systems analysis, it may now be possible to map a timeline where reasonable insertion of CNT usage can be planned to allow focused efforts needed to develop the material for phased insertion as its maturation allows. Successful demonstrations of its use can prove technology readiness. The desired state of the technology’s maturation can be reached sooner when there is a mission pull with sufficient requirements for realistic evaluation of the technology’s capabilities and limitations.

Space Mission Campaign

Future NASA missions range in scale from launching small cubesats with mass requirements ranging from one kilogram for missions to low Earth orbit (LEO) to landing a 20-40 ton payload on Mars for a human Mars campaign. The latter mission is very complex and beyond NASA’s current budget profile. For example, the current human Mars reference campaign (Human Exploration, 2009) calls for 9 heavy launch vehicles (LV) to carry payloads and one smaller LV to carry the crew (total of 849 tons in LEO). Technology advances in materials such as CNTs can enable more affordable systems architectures if advances can contribute to a significant reduction in the numbers and sizes of required LVs and payloads.

The committee on the planetary science decadal survey (Vision and Voyages, 2011) has identified and documented potential robotics missions. The committee recommended splitting the potential missions into small (<$500 million), medium (<$1.0 billion), and large (>$1.0 billion) classes. Table 1 shows a list of potential robotic missions. These missions are complex and have to operate in extremely harsh environments ranging from Moon's poles to Saturn's moon Titan, and they provide potential opportunities for CNT applications. Early insertion opportunities in some missions might be useful proving grounds for the benefits of CNTs in more benign load bearing applications.

Table 1. List of Potential Robotic Missions

Mission Categories	Potential Missions	Destinations
Small < $0.5 Billion	Icebreaker Life (Mars)	Mars
	Mars-Moons Exploration, Reconnaissance and Landed Investigation (MERLIN)	Mars
	Phobos And Deimos & Mars Environment (PADME)	Mars
	Phobos And Deimos Origin Assessment (PANDORA)	Mars
	Advanced Jupiter Asteroid eXplorer (AJAX)	Jupiter
	Trojan asteroids (Lucy)	Jupiter
	Io Volcano Observer (IVO)	Jupiter
	Enceladus Life Finder (ELF)	Saturn
	Journey to Enceladus and Titan(JET)	Saturn
	RAdar at VENus (RAVEN)	Venus
	Venus Atmosphere and Surface Explorer (VASE)	Venus
	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS)	Venus
Medium < $1.0 Billion	Comet Surface Sample Return	Comet
	Lunar South Pole-Aitken Basin Sample Return	Lunar
	Saturn Probe	Saturn
	Trojan Tour and Rendezvous	asteroids
	Venus In Situ Explorer	Venus
	Lunar Geophysical Network	Moon
	Io Observer	Jupiter Moon Io
Large > $1.0 Billion	Mars Astrobiology Explorer-Cacher (MAX-C)	Mars
	Jupiter Europa Orbiter	Jupiter Moon Europa
	Saturn Enceladus Orbiter	Saturn Moon Enceladus
	Uranus Orbiter and Probe	Uranus
	Venus Climate Mission	Venus

Systems Analysis

Aerospace systems are generally complex and comprised of many interconnected subsystems. Changes in one part of the system may exhibit anticipated and/or unforeseen impacts on other parts of the system. The impact of novel technology such as CNTs on a complex system is exceedingly difficult to assess by intuition or hunches. Its impact at the systems level may not be anticipated or can be missed entirely. Systems analysis provides a systematic approach for analyzing this complex problem and assessing the influence of this emerging material from a systems level perspective.

Systems analysis is a multidisciplinary activity, which is used to partition a system into its subsystems for purposes of studying how each subsystem interacts with other subsystems. The focus is on the systems as a whole and the relationship among subsystems, their interdependency, and their impact on the overall problem. Developing system analysis capability requires a significant initial effort. The results will help identify critical drivers and high payoff technologies (Samareh et al., 2014; Polsgrove et al., 2016) through system sensitivity analysis. Two approaches that are relevant to space applications are discussed next: gear ratio and a simple rocket equation that are useful in providing the big picture, and integrated systems analysis for more detailed systems level assessment.

Gear Ratio and Rocket Equation

A simple rocket equation is useful for rapid systems assessment. The equation in its simplest form is:

$$\frac{M_{\text{Payload}} + M_{\text{Sys}}}{M_0} = e^{\left(\frac{-\Delta V}{g_{\text{Earth}} * Isp}\right)}, \qquad [1]$$

$$M_0 = M_{\text{Prop}} + M_{\text{Sys}} + M_{\text{Payload}} \qquad [2]$$

where M_0, M_{Prop}, M_{Sys}, and M_{Payload} are the initial, propellant, system, and payload mass components, respectively. The terms ΔV, g_{Earth}, and I_{sp} are the change in vehicle velocity, specific impulse (measure of rocket efficiency), and constant Earth gravity, respectively. The ΔV is unique for each destination and depends on planetary positions. For example, ΔV for a trip from Earth surface to low Earth orbit is ~9.4 km/s. The ΔV values can be 20-30 km/s for missions to outer planets. CNTs could have potential impacts on payload, system mass, and *Isp*.

Gear ratio is a figure of merit for mission design; it represents the initial units of mass required to deliver one unit of useful payload to a designation (M_0/M_{Payload}). Figure 1 shows contour lines for gear ratio as function of ΔV and system mass fraction (M_{sys}/M_0). For Example, it takes 36 units of mass to deliver one unit of payload to low Earth orbit (ΔV ~9.4 km/s and M_{sys}/M_0 of 8%) for single stage rockets using liquid hydrogen and oxygen (*Isp* of 430 s). Using multi-stage rockets improves the gear ratio. The Saturn V shown in Fig. 1 uses three stages with a gear ratio of ~20. The dotted line in Fig. 1 shows the limit of a single stage to orbit concept.

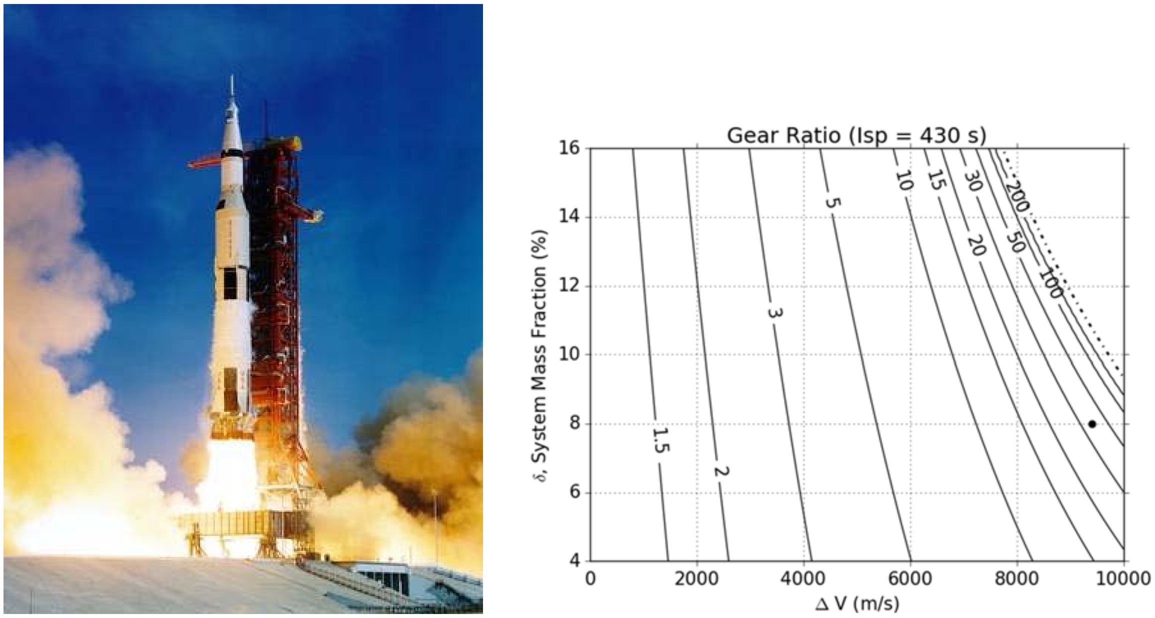

Figure 1. Saturn V (left) and gear ratio contours (right).

Engine improvements through CNT applications and/or nanotube propellant additive could potentially improve engine performance, I_{sp}. Using the example in the previous paragraph, if CNT performance improves I_{sp} from 430 s to 440 s (2.3% increase), the gear ratio will increase by 16.7%. Of course, these improvements strongly depend on ΔV (improvements get better as travel distance increases).

A system mass fraction reduction through CNTs application could potentially enable a mission. For example, if CNT application can reduce system mass fraction from 10% to 8%—a reduction of 2% in system mass—the gear ratio will be reduced from 130 to 36, a 3.6 fold savings. These savings grow exponentially with ΔV and M_{sys}/M_0; missions to outer planets require much larger ΔV and have potential for significant reduction. For example, the gear ratio for a lunar round trip is 500 (Gordon, 2007). The gear ratio to land a payload on Mars—using Mars Science Laboratory (MSL) as an example—is 372. If the Mars atmosphere were not used as an aerodynamic break, the gear ratio would increase to 500 (Gordon, 2007). The Voyager spacecraft that NASA launched in 1977 was the first human-made object to enter interstellar space. The gear ratio for Voyager is approximately 820. The gear ratio for a trip to Mars and return is 5000 (Gordon, 2007). This means that any mass savings on Earth return entry vehicles would be magnified by a factor of 5000.

Integrated Systems Analysis

While the rocket equation provides a good first order estimate, it may not be adequate for complex missions. For example, human Mars entry, descent, and landing (EDL) is one of the most critical segments of the entire mission. This segment starts at Mars arrival, goes through aerocapture, and ends with Mars landing. During aerocapture and EDL, the vehicle goes through extreme aerothermodynamic heating and mechanical loads. The system must be designed to survive both aerocapture and EDL. The hypersonic inflatable aerodynamic decelerator (HIAD) is one of the several candidates that NASA is considering (Polsgrove et al., 2016). The current system consists of two separate HIADs with mass of 4-5 t for each aeroshell. This is primarily due to concerns that a single HIAD may not survive two atmospheric entries with weeks or months in between. One approach to reduce system mass is the use of advanced materials such as CNTs. System analysis of human Mars EDL indicates that the gear ratio between Mars arrival and landing is between 2.5 and 3. Saving one kilogram of landed mass will result in 2.5-3 kg mass reduction at Mars arrival, translating into much bigger mass savings for the launch system on Earth. A far more effective approach is to use advanced materials to design a single HIAD that can survive two atmospheric entries. This approach could result in significant mass savings, providing a paradigm shift that has significant impact on the entire human Mars architecture. The next section provides a discussion on opportunities and challenges for CNT insertion into applications that can benefit from significant mass savings.

Opportunities and Challenges

Since the biggest payoff for mass savings is attained in missions having high gear ratio, the applications to be discussed will be limited to those that support such missions. The following subsections will cover potential CNTs applications that can improve I_{sp} performance and reduce payload mass and system mass fraction. These improvements could be further magnified, especially for missions to distant planetary bodies. It should be noted that these application opportunities require further research to develop credible material properties to yield quantified benefits for a given mission. The following applications appear in order of their potential importance.

Human Mars Campaign

Figure 2 shows the current design concept for the human Mars arrival vehicle. It consists of an entry system (e.g., Hypersonic Inflatable Aerodynamic Decelerator, HIAD), cargo (e.g., Mars ascent vehicle, or MAV), and a lander (Polsgrove et al., 2015). Although there are several cargo and entry system options, the lander concept remains the same for all cargo and entry system options. Figure 3 shows mass breakdown for the arrival configuration shown in Fig. 2.

As with most large propulsion systems, the Mars lander depends on a pump-fed system, operating the propellant tanks at tens of psi. Heritage tanks are very thin and subject to the manufacturability limit of minimum gauge, especially since current tank concepts have been highly optimized. For example, the space shuttle external tank (ET) has a dry mass fraction of 3.48% (dry mass divided by wet mass), which is lower than the dry mass fraction for a soda can (3.7%). The ET operated at -252 °C and 32-34 psi and maximum flow of 47,365 US gal/min. This highly optimized ET concept has lower mass, but it comes at a higher life cycle cost. Two challenges that CNTs have to overcome for them to be used in propellant tanks are that both tank thickness and mass are linearly proportional to tank pressure (Humble et al., 1995).

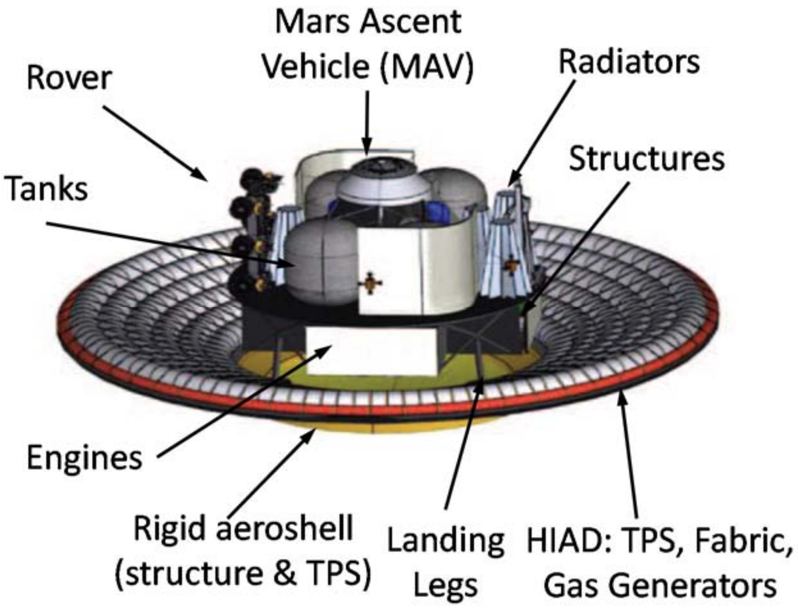

Fig. 2 Baseline TMI Arrival Configurations

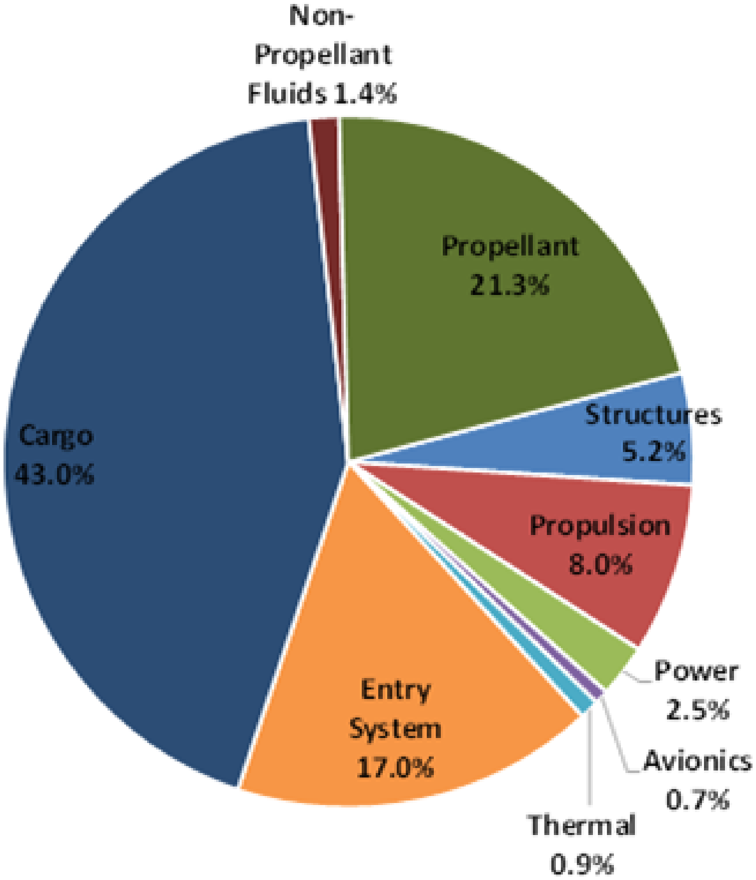

Fig. 3 Configuration Mass Breakdown

In order to assess the benefits of CNTs for lander tanks, a systems analysis study was performed using the trans-Mars injection (TMI) system mass as a figure of merit. The TMI mass is the vehicle mass delivered to Mars arrival orbit for a given payload. Figure 4 shows TMI percent mass increments above baseline mass as a function of tank strength factor (ratio of specific strength of advanced concept over the baseline), assuming a fixed payload mass delivered to the Martian surface. The blue circles represent improvements for the baseline pump-fed tank design. Increasing material performance even by a factor 5 has very little impact on the overall system performance (TMI mass).

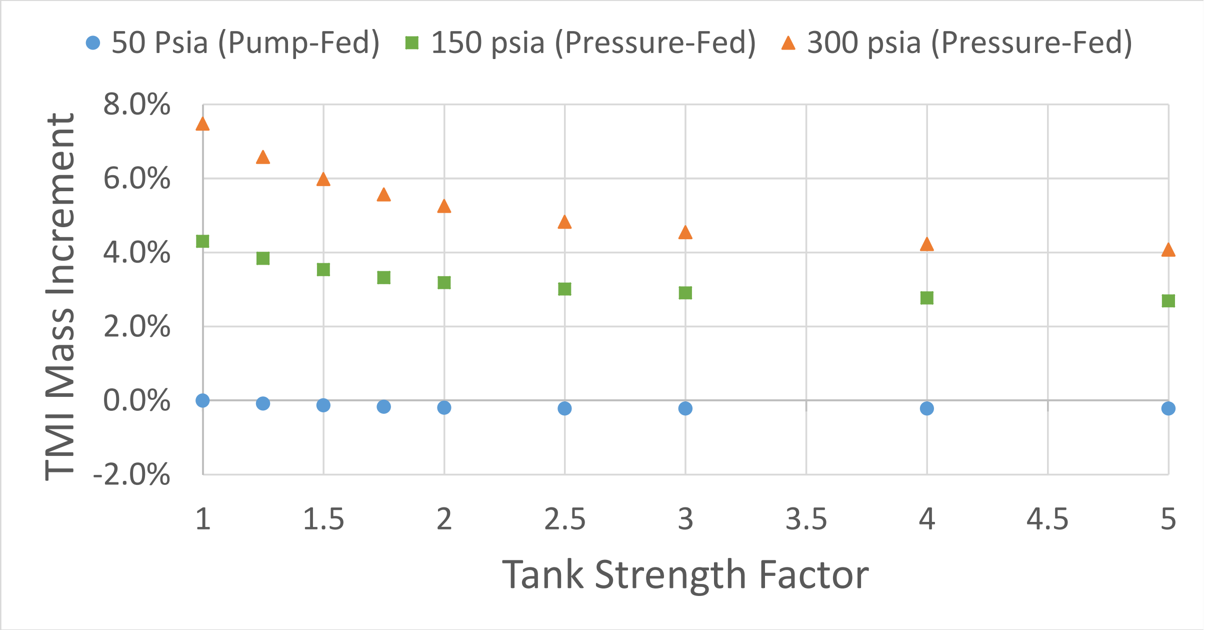

Figure 4. Impact of Advanced Materials on TMI Mass for Mars Lander

An alternative approach is to eliminate the need for pumps that are complex and have many thousands of rapidly moving parts under considerable stress. Pressure-fed systems do not require pumps and rely solely on tank pressure to operate. The tank pressure for these systems is in the order of 100s to 1000s of psi, which moves the designs limited by minimum gauge to much thicker tanks that can benefit from high tensile strength materials. The pump typically accounts for about 20 percent of the cost of an engine (Morgan, 1989). Chakroborty and Bauer (2004) concluded that the pressure-fed designs are heavier than the traditional pump-fed designs if they are constructed using the same materials. However, the introduction of composite tanks, high performance pressurization systems, and low-cost ablative engines can enable pressure-fed design solutions at a significantly lower cost and higher reliability compared to the pump-fed options. In this case, high strength CNTs provide an opportunity for game-changing concept, where there could be a significant improvement for the mission cost and risk.

The challenge for CNTs is illustrated in Fig. 4. For example, a factor of two improvement in material strength would result in a pressure-fed system operating at 150 psia with a 3.2% penalty in the TMI mass with an estimated benefit of 20% reduction in cost with far better reliability. This estimate is very conservative and it does not account for the improvements in the pressurization systems. As shown in Fig. 4, application of CNTs expands the design space allowing effective trades between mass, cost, and reliability.

This type of analysis needs to be undertaken to provide mechanical properties that can guide the development of CNTs for specific applications. In addition, to realize benefits of CNTs in lightweight structures for space applications, they will need to be in formats that enable their use in the fabrication of large structures. It should be noted that carbon fiber reinforced polymer (CFRP) composites are state of the art for lightweight structures, so CNTs will have to exhibit superior mechanical properties that justify their use in place of CFRPs. These include higher specific tensile properties and better interlaminar properties for enhanced damage tolerance. Application of CNTs to other parts of the propulsion system (e.g., engine and nozzle) could result in further improvements.

Rocket Motors

Improving combustion efficiency requires higher combustion temperature and pressure, which are generally limited by engine design. Liquid-fueled rocket engine combustion chamber liners are regeneratively cooled to maintain a high heat flux so that the liner surface temperatures are well below the melting point of the liner. Bhat et al. (2013) made an effort to improve the combustion chamber liners in liquid rocket engines using nanotechnology. Their approach involved embedding high thermal conductivity multiwall carbon nanotubes (MWCNTs) and diamond (D) particles in the NARloy-Z matrix using powder metallurgy techniques. The effort was not successful, and it was traced to their supply of MWCNTs that had a low thermal conductivity. This application provides opportunities for reduction in system mass fraction and engine efficiency for most mission using chemical propulsion. As CNTs are now available in formats possessing higher thermal conductivity, this application may be worth revisiting. The new study can examine the feasibility of hybrid materials to reduce mass while improving engine efficiency.

Solar sail

Solar sails are non-rocket spacecraft that use radiation pressure from sunlight for primary propulsion (Bolonkin, 2006). The sails are several meters wide and are constructed with highly reflective ultrathin materials, typically aluminized Kapton. Figure 5 shows a nanosatellite that deployed NASA's first-ever solar sail in low-Earth orbit (NASA's Nanosail-D, 2011; Solar Sail Stunner, 2011). The solar sail successfully completed its Earth orbiting mission. A NASA research team is developing another project that will test solar sail deployment. The Asteroid-Surveying CubeSat Near-Earth Asteroid (NEA) Scout project is set to launch in July 2018 and will perform a reconnaissance flyby of an asteroid (Near Earth Asteroid, 2017).


Fig. 5 NanoSail D

Efficiency of solar sails is measured in terms of spacecraft acceleration that is inversely proportional with sail areal density (Bolonkin, 2006). Traditional sails consist of a reflecting layer to absorb solar pressure and a layer to emit heat to maintain the sail's temperature at operating levels. Aluminized Mylar and Kapton are commercially available materials with areal density of 7 g/m^2. Carbon nanotubes membranes can be used as a monolayer capable of reflecting and emitting layer (Santoli, 2010). The nanotube sheets will need to be so thin that a square kilometer of solar sail would weigh only 27 kilograms (0.027 g/m^2 (Zhang et al., 2005)).

Spieth and Zubrin (1999) report that current propulsive methods would take over a decade to reach Pluto and are impractical to reach interstellar space. However, based on some assumptions made in their calculations for sail acceleration, if the reflectivity of CNTs can be enhanced by doping without significantly increasing mass, such a sail could reach Pluto in days and our nearest star in a few decades. The Starshot project (Overbye, 2016) is another interesting concept based on using thin sails to travel at 15%-20% of speed light. The project plans to get to Alpha Centauri in 20 years. The project is funded by the Yuri Milner, a Russian internet entrepreneur, and has support of Stephen Hawking, the English cosmologist.

In order realize a CNT-based solar sail mission, there needs to be research and technology development to address critical questions regarding scalability. For example, is it possible to fabricate very low density, highly reflective CNT sheets at the scale needed for the solar sails? At these scales, is it possible to retain the desirable properties of CNTs that were used to project their benefit in this application?

Propellant Additives

Propellants are energetic materials used to generate thrust in rockets. Their performance is measured by the ratio of thrust to propellant flow rate. Combustion efficiency is higher if the higher thrust is generated for the same flow rate. Improvements in combustion efficiency (Isp) could thus result in substantial mass reduction for the overall mission (see Eq. 1), considering smaller volumes of high efficiency propellant are required, along with reduction of the associated infrastructure needed to contain the propellant. For the problem shown in Fig. 1 (ΔV of 9400 m/s and system mass fraction of 0.8%), a 5% improvement in Isp results in a reduction of gear ratio from 36 to 25. The electrical and thermal properties that accompany high surface area CNT powders can contribute to such a mass reduction even at very low concentrations (Yan et al., 2016). Kappagantula et al. (2015) studied the influence of CNTs on the ignition delay and combustion performance. They demonstrated a low percolation threshold for CNTs to influence the characteristics of energetic materials. With 1.5% by weight addition of carbon nanotubes, the flame speed of the energetic thin films increased by 440%, electrical conductance by two orders of magnitude and ignition delay decreased by 87.2% relative to the undoped baseline material. Um et al. (2016) found that the exothermic reaction speeds of energetic materials they studied increased ~100x when they were bound to vertically aligned CNTs having high thermal conductivity. Similar reports of acceleration of reaction rates by mixing CNTs with pyrotechnic materials have been published (Yan et al., 2016). Studies will have to be conducted on scalability of highly efficient propellant formulations, including considerations for safe handling of the propellant given the enhanced reactivity suggested in the above reports.

Whipple Shield

The Whipple shield is a shield to protect spacecraft from Micrometeoroid and Orbital Debris (MMOD) impact. The MMOD can impact spacecraft at hypervelocities of 3-18 km/s with catastrophic results. The Thermal, Radiation and Impact Protective Shields (TRIPS) concept discussed early is one potential CNT application. Khatiwada et al. (2013) assessed the use for nanocomposites as bumper shields and as rear walls in Whipple shield configurations at impact velocities in the 6.5-7 km/s range. Their results suggest that CNTs may contribute to enhanced impact resistance in a composite structure when CNT buckypaper is integrated into the composite. Design configurations for CNT containing composites may be worth exploring further considering the results from this study (Khatiwada, 2014). Any mass saving will help reduce system mass fraction, and the reduction will be further magnified as shown in Fig. 1.

Thermal Protection System (TPS)

The TPS systems used in many spacecraft components range from simple multi-layer insulation blankets to protect spacecraft subcomponents to ablative TPS required for atmospheric entries. The TPS mass fraction (ratio of TPS mass to aeroshell mass) could range from 2.8% for Viking Mars entry (with heat flux of ~25 W/cm^2) to 50% for Galileo Jupiter entry (~30,000 W/cm^2) (Laub et al., 2008).

Studies involving the use of lightly doped composite matrix resins suggest the potential for these nanocomposites to enhance thermal protection system performance. Nikolaev et al. (2006) proposed the use of CNTs to enhance carbon-phenolic ablator material. They showed that nanotubes can improve strength of phenolic resin that binds carbon fibers together and also improve micrometeoroid tolerance. Tate et al. (2013) proposed exploiting the high surface-area-to-volume ratio of CNTs for ablative and reinforcement materials for thermal protection systems. Their results show that the addition of MWCNT resulted in decrease in percentage TPS mass loss due to ablation. The recession of the control composite specimen was 0.83 mm, whereas it was 0.38 mm for nanocomposites containing 2 % MWCNT. Their results indicated that increases in MWCNT content improved ablation and insulation performance of nanocomposites. Further investigations to confirm the above results in larger samples subjected to the rigors of tests typically conducted for TPS are needed. If the performance characteristics observed in laboratory scale experiments can be retained in larger structures, it may be possible to reduce the amount of material used for these applications to achieve measureable systems benefits in systems mass savings.

Surface Coatings

Electrical and electromagnetic properties of CNTs have supported near term space applications. NASA's Juno spacecraft (Houston, 2016) was designed to travel through strong radiation belts en route to Jupiter. This required a stronger-than-usual electrostatic discharge protection, replacing traditional aluminum foil bonded to the spacecraft surface. Rawal et al. (2013) describes applications of CNTs based composite components for Juno spacecraft to protect flight system's attitude control motor struts and the main engine housing. Juno completed its five-year travel and arrived safely at Jupiter on July 4, 2016.

Space applications for CNT coatings may be extended to their utility in mitigating threats posed to satellites by ground-based directed energy weapons. Huntington (2007) analyzed using CNT membranes for electromagnetic shielding and to enhance lateral thermal conductivity. The role of surface coatings in improving satellite thermal control and electrical conductivity, radiation hardness of commercial-grade microprocessors for use in satellites, and hardening satellite structures was also discussed. Use of CNTs is being suggested for aircraft lightning strike protection. Current solutions rely on the conductivity of metallic meshes. However, if CNTs can attain the required levels of conductivity, without requiring metallic doping, significant mass savings can be attained (Gagné & Therriault, 2014), and their use can be extended to protecting spacecraft from severe electromagnetic events.

Thermal Radiators

Spacecraft thermal management systems are a critical element of space operation. Thermal management relies on efficient heat transfer to maintain devices within operating range. The system may consist of radiators, heat pipes, insulation, and heaters. They are divided into three categories: electronic components, propulsion elements, and payload thermal management. Poor thermal management could result in equipment with shortened life, performance degradation, and reduced reliability. Traditional mitigation approaches typically add significant mass to the system.

Current radiators are made of conductive materials such as aluminum or copper to extract heat and dissipate it. For high-power nuclear-electric spacecraft, the radiator can account for 40% or more of the power system mass and a large fraction of the total vehicle mass (Hyers et al., 2012). Since CNTs are efficient heat conductors, they may enhance the efficiency of thermal management systems. Challenges in employing CNTs in this role are around the directionality of thermal conductivity. The radiators will have to be designed with considerations for anisotropic thermal conductivity of this material. Some recent examples of approaches to enhance through thickness thermal conductivities involve using CNT in hybrid composite structures (Yang et al., 2016; Kang et al., 2016). While these approaches have yet to be scaled up, the ability to do so promises to reduce mass significantly considering the much lower densities of hybrid composites used here relative to SOA metallic solutions.

Electrodynamic Tether (EDT)

The EDT systems generate thrust through Lorentz-force interactions as a conductive tether crosses the planet's magnetic field at orbital velocity, converting orbital kinetic energy to electrical power. When stored electrical power is supplied back to the tether, the tether's electrodynamic force pushes against the planet magnetic field, raising the spacecraft to a higher orbit. The tether is kept taut by the gravity gradient field. EDT systems eliminate the need for propellant, and they overcome the limitations posed by the rocket equation. The EDT systems can be used to decommission satellites or boost them to higher orbits.

Several EDT concepts have been designed and flown with different levels of success. The Propulsion using Electrodynamics (PROPEL) experiment shown in Fig. 6 was designed to have both boost and deboost capabilities using a single tether (Gilchrist et al., 2012). Johnson and Herrmann (1998) proposed using EDT to reboost the International Space Station. Their proposed system could generate 0.5-0.8 N for 5-10 kW (ISS aerodynamic drag is 0.2-1.1 N). The system mass is less than 200 kg, but it could save 2-4 t of propellant. Gallagher et al. (1998) have proposed an EDT concept for Jupiter, where the planet has a strong magnetic field, and the mass of the planet dictates high orbital velocities resulting in as high

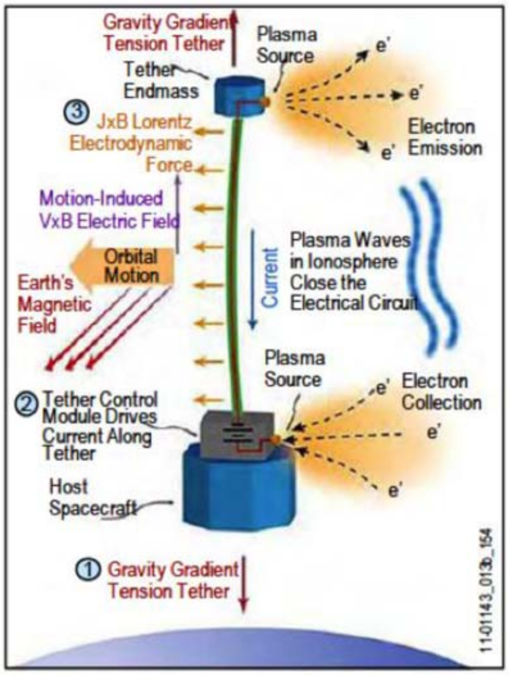

Fig. 6 PROPEL concept

as 50 N and power levels as high as one MW.

Figure 7 shows the Tethered Satellite System (TSS-1R) tested in 1996, during which a 20-km tether broke (Szalai et al., 1996). The tether was a copper braid wound around a nylon string. It was encased in Teflon-like insulation, with an outer cover of Kevlar, all this inside a nylon sheath (Fig. 7). The cause of failure turned out to be the innermost core, made of a porous material, which during its manufacture trapped many bubbles of air at atmospheric pressure. The nature of the break suggested it was not caused by excessive tension, but rather that an electric current had melted the tether.

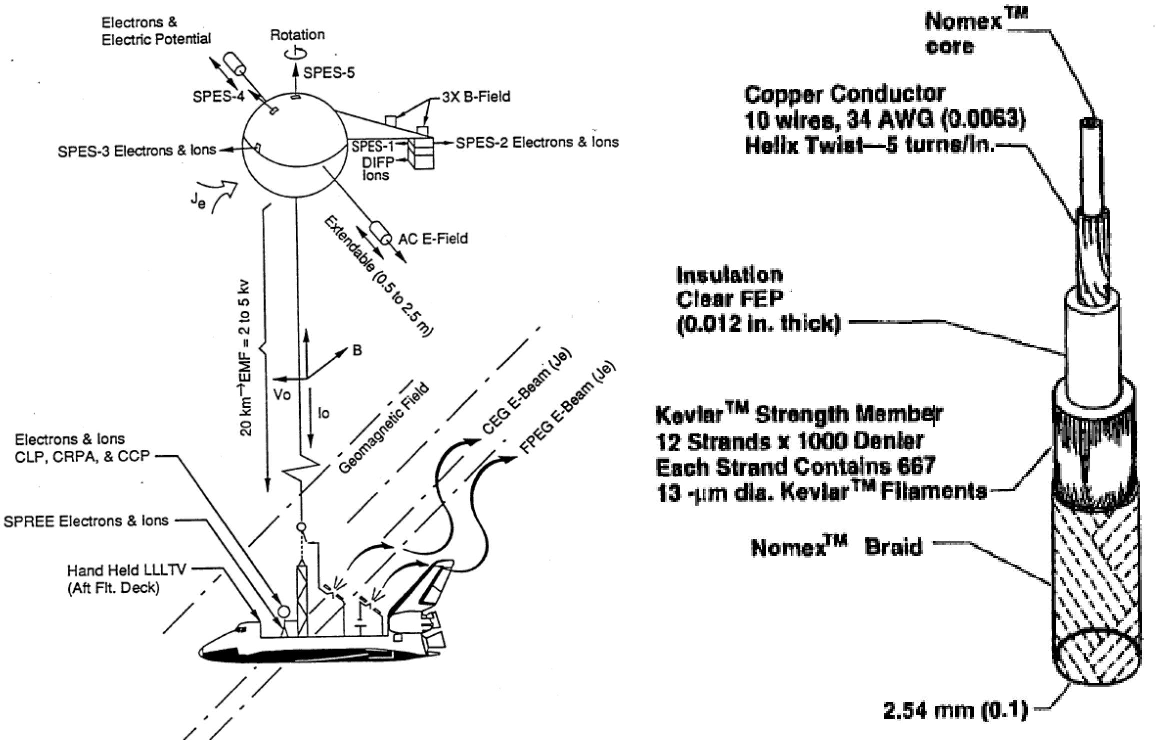

Fig. 7 TSS-1R EDT configuration (Szalai et al. 1996): deployment (left), tether (right)

Some EDT designs may require a field collector and/or emitter. Okawa et al. (2005) have proposed using CNT for field emission array. Bell et al. (2013) present a concept for Miniature Tether Electrodynamics Experiment (MiTEE) for ultra-small satellites. They identified arrays of vertically aligned carbon nanotubes that have lower power consumption requirements for electron collection and emission

The EDT systems have two main components: the tether and electron-collecting/emitting device. Depending on the applications, the tether could be a simple wire, coaxial cable, or tape. The tether must be efficient electrical conductors, mechanically strong, and lightweight. The high aspect ratio of CNTs combined with their high electrical conductivity and excellent tensile mechanical properties make them good candidates for EDT applications.

CNT applications for EDT also need to be resistant to corrosion from atomic oxygen present in the upper atmosphere and tolerate power surges, large vibrations, and micrometeorite impacts. While many of the desired properties for CNT tethers are surpassed on the nanoscale, they need to be retained on the macroscale in order to be considered for this application. Recent progress in scaling up the manufacturing of these high ampacity materials with specific conductivity beginning to approach that of copper brings the promise of using them in lightweight tether applications closer to reality (DexMat Carbon Nanotube products; Wang et al., 2014).

Concluding Remarks

After introduction of carbon nanotubes over two decades ago, the application of CNTs for space missions remains a challenge. Carbon nanotubes are well studied at microscopic levels, but there is still a lack of understanding about their behavior in macroscopic applications. In order to implement CNTs for space missions, CNTs need to be characterized for their effectiveness at macroscopic levels, manufactured at a large scale, and fabricated reliably into large space structures. From a systems analysis perspective, potential aerospace applications need to be identified and their benefits quantified at the systems level.

This paper discussed some of the potential space applications for carbon nanotubes and provided a simple engineering level approach to quantify the benefits. There are many other potential space applications of CNTs such as carbon-nanotube resin mirror for optic in a CubeSat telescope. Other potential space CNTs applications are: hypersonic inflatable aerodynamics decelerators (HIADs), adaptive deployable entry and placement technology (ADEPT), high altitude long endurance vehicles (e.g., Mars and Venus airplanes), in-situ resource utilization (ISRU), planetary rovers, parachutes, flywheels, tires, space suits, landing mechanisms, sensors, 3D printing, purification, filtration, antennas, batteries, and habitats.

It is recommended that CNT subject matter experts work closely with aerospace systems designers to close the gap between innovative material concepts and realistic aerospace applications. The promise of CNTs can be only fully realized with close collaborations between materials and aerospace systems experts.

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