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AIR WAR COLLEGE

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# NANOTECHNOLOGY –

# ENABLING FUTURE SPACE VIABILITY

By

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A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements

18 March 2009

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **MAR 2009** | **N/A** | **-** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Nanotechnology Enabling Future Space Viability** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Air War College Maxwell Air Force Base, Alabama** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
| **unclassified** | **unclassified** | **unclassified** | **SAR** | **56** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

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# Contents

## Abstract

The U.S. is at a critical juncture in space and national security leaders should take heed. Global competitors have begun to rapidly erode the U.S.' lead in space supremacy. The employment of U.S. land, sea, air, and cyber warfighting capabilities in the nation's defense are critically dependent today on the availability, reliability, and viability of U.S. space assets and always will be. Henceforth, space is vital to the nation's security now and in the future.

The biggest challenges the U.S. faces in the acquisition and launch of additional secure, advanced, and hardened space assets are their massive cost coupled with their enormous weight, the ability to provide lift, to supply extended power, and to manage heat. This crossroad requires innovation, thinking out-of-the-box, and a focus on exponential technological possibilities. Nanotechnology, a disruptive technology ripe for exploitation, is an underlying technology that makes other things possible. It is the likely driving force of the next industrial revolution.

The properties of nanotechnology-enabled systems and materials are ideal for space. In the near term, these space systems will have significantly enhanced flexibility, robustness, and performance capabilities with reduced costs. The high payoffs include ultra small sensors, communication and navigation, power sources, and propulsion; dramatically reduced emission, mass, volume, heat, and power and fuel consumption; easily reconfigurable, autonomous systems; and multifunctioning single chip satellites. In the longer-term, they may include systems with 1,000 times the performance and weapon systems enabled by nanotechnology.

Space is the future frontier[1] once again. The U.S. must take decisive action before the nation's security posture is irrevocably weakened. This paper contends that aggressive development of nanotechnology-enabled space systems by the U.S. today has the potential to facilitate the nation's future space viability and dominance in 2035 and beyond.

## Biography

Lieutenant Colonel Eva S. Jenkins received her commission in 1988 through the Reserve Officers' Training Corps as a Distinguished Graduate. She is a career intelligence officer, an Air Force instructor, and a European, Eurasian, and North Atlantic Treaty Organization area specialist who is fluent in Slovak and familiar with Czech and French.

Colonel Jenkins has served: at an intelligence field site in Italy; on the Headquarters Air Intelligence Agency staff; as a Reserve Officer Training Corps Instructor; on the Joint Staff Directorate of Intelligence staff; on the Defense Intelligence Agency Director's Special Projects staff; and as a National Security Agency Director's Fellow. After completing a Research Fellowship for the Strategic Intelligence Research Center at the Joint Military Intelligence College, the Defense Intelligence Agency published her book *Military Intel-Sharing Relationships among NATO Allies in Support of the Global War on Terrorism* in 2004. She later served as the Intelligence Director, Space and Missile Systems Center, Los Angeles Air Force Base, California and 301st Intelligence Squadron Commander while dual-hatted as Director of Mission Operations at the joint Misawa Security Operations Center, Misawa Air Base, Japan.

Colonel Jenkins received her Bachelor of Science degree in mathematics from the University of Miami in Florida in 1988, a Master of Arts degree in computer resources and information management from Webster University in Missouri in 1994, and a Doctorate of Philosophy Degree in international studies in 2003 also from the University of Miami. Her doctoral dissertation was published in 2004 under the title *Slovakia's Journey to NATO Membership* in English and Slovak. Colonel Jenkins is married to Robert Jenkins of Miami, Florida. They have a seven-year old daughter, Katarina Eloise.

# Section One

# Introduction

The U.S. is at a critical juncture in space and national security leaders should take heed. While the U.S. has maintained space supremacy since the dawn of the space age, global competitors have begun to rapidly erode that lead. These global competitors, to include state and non-state actors, have the capability to exploit the space domain's immense vulnerabilities. Russia and China have clearly demonstrated a direct kinetic kill anti-satellite capability. In addition, several other nations and non-state actors are working on active, effective anti-satellite offensive warfare capabilities. Furthermore, the recent collision between a U.S. and Russian satellite highlights space's increasing vulnerabilities.

It is not a secret that the employment of U.S. land, sea, air, and cyber warfighting capabilities in the defense of the nation are critically dependent on the availability, reliability, and viability of U.S. space assets and always will be. Henceforth, space is vital to the national security of the U.S. today as it will continue to be so tomorrow. There are no viable alternatives to space systems and threats from global competitors are real. The U.S. is truly at a crossroads. The nation must overcome its greatest challenges in space and capitalize on disruptive and emerging technologies before it is too late.

The greatest challenges the U.S. faces today in the acquisition and launch of additional advanced, hardened, and secure space assets are their massive cost coupled with their enormous weight, the ability to provide lift, to supply extended power, and to manage heat. Fortunately, the potential solutions are many and varied. The U.S. can seek to: reduce the cost of launch;

improve spacecraft performance of spacecraft; decrease the cost of power consumption and increase longevity; expand spacecraft functionality; decrease the cost of communications while expanding life expectancies and currency; or reduce spacecraft cost in dollars per kilogram for the function and performance it provides. Alternately, the U.S. can exponentially improve the spacecraft function and performance so that the spacecraft capabilities far outweigh the cost. For this to occur, the U.S. must renew its commitment to the advanced research and development of new technologies and restore its commitment to space.

This historic crossroads requires innovation, thinking out-of-the-box, and focusing on the vast array of exponential technological possibilities. Rapidly advancing technologies with the ability to transform and revolutionize virtually every industry, to include space, are ripe for exploitation. Genetics, robotics, information technology, and nanotechnology are truly transformative technologies with the potential to impact national security both positively and negatively. The technological advances predicted in the coming years are expected to exponentially surpass the advances seen during the past century. But of the four, nanotechnology, the *underlying technology that makes other things possible*, is the key to future space viability and dominance. Nanotechnology is the research and technology development at the 1- to 100th nanometer scale, the creation and use of structures that have novel properties because of their small size, and the ability to control or manipulate at the atomic scale. Nanotechnology may very well be the driving force of the next industrial revolution.

The properties of nanotechnology-enabled materials are ideal for space. As such, nanotechnology holds the key to transforming the space domain and the major driving force in the expansion of space capabilities. Over 60 nations have established nanotechnology initiatives and over 4,000 companies and research institutes are working on nanotechnology developments worldwide. In the near term, nanotechnology-enabled space systems will have significantly enhanced flexibility, robustness, and performance capabilities and eventual reductions in costs. The high payoffs include ultra small sensors, communication and navigation, power sources, and propulsion; dramatically reduced emissions, mass, volume, heat, and power and fuel consumption; easily reconfigurable, autonomous systems; and single chip satellites with multiple capabilities. In the longer-term, the nanotechnology-enabled systems will likely provide space systems with 1,000 times the performance of today's systems; weapon systems at the warfighters' fingertips enabled by nanotechnology; and carbon nanotube space elevators, among others. There is no doubt that these revolutionary systems will be enabled by nanotechnology and will be employed in space. Whether they will be routinely employed in space by the U.S. or by someone else is yet to be seen. The U.S. must take decisive action before the nation's security posture is irrevocably weakened. The development of the future frontier[2] has only just begun.

This paper briefly explores the importance of space today to the U.S. and surveys its most obvious vulnerabilities. Second, it examines the landscape of advancing technologies, focuses in on the easily forgotten game changer—nanotechnology—and its practical space applications, and explores who the leading competitors in the realm of nanotechnology research and development are around the world. Third, this paper envisions a space enabled by nanotechnology in the future by exploring real near-term possibilities, surveying long-term predictions, and addressing the impact of nanotechnology-enabled space on the future of U.S. national security in the context of four alternate future scenarios. At the conclusion, this paper contends that aggressive development of nanotechnology-enabled space systems today has the potential to facilitate future space viability and dominance in 2035 and beyond.

## Section Two

## Space Today (2009)

The space age began over half a century ago. Since then the world witnessed the development of astounding technological advancements in the space domain and the global space industry experienced enormous growth. In 2007 the overall worth of the commercial, civil and military space industry reached nearly $220 billion.[3] The global financial crisis, which began in October of 2008 and remains in a tailspin today, will likely precipitate an industry slowdown at least in the short-term. However, because space has become an integral part of the lives of so many around the world, this recent economic downturn will likely have little effect on the long-term future of space development.

**Importance**. The contributions of space-enabled technologies touch billions of people every day in areas such as television broadcasting, telephone services, commercial aviation and shipping, train transportation, police and fire emergency services, personal vehicle navigation, finance and banking, product tracking, agriculture, and so much more.[4] While important to our daily lives, space is also critical to the nation's security and defense as the Department of Homeland Security (DHS), the entire Department of Defense (DoD), and key federal agencies depend on space assets as they protect the U.S. and its citizens and American interests around the world.

The value of space or its importance to the U.S. economy, military, and overall security is lost on many. Furthermore, not everyone agrees with the assertions that space power is critical to the U.S., that we are increasingly more dependent on space assets, and that the nation will become even more vulnerable if we do not retain dominance in space. The article "Spacepower: A Strategic Assessment and Way Forward" warns that "…spacepower remains misunderstood, underdeveloped and underexploited…Spacepower offers the prospect of tremendous benefits to humanity…Failure to understand the nature of spacepower and how to wield it productively could lead to serious miscalculations and tragic consequences."[5] Fortunately, some of the nation's best scientists, engineers, researchers and leaders in the public, private, and academic sectors are working on issues and developments that will contribute to the U.S.' ability to avoid future catastrophic consequences in space. But can more be done?

A May 2003 Report of the Defense Science Board and Air Force Scientific Advisory Board Joint Task Force on Acquisition on National Security Space Programs conveyed in its findings that "*U.S. national security is critically dependent upon space* capabilities and that dependence will continue to grow."[6] The report stated that our nation must continue to be able to monitor worldwide activities, transfer massive amounts of data, and provide global force projection. It added that the nation requires "robust space assets" to be able to meet these national requirements effectively and that there is "no viable alternative to the unique capabilities that space systems provide."[7] In 2005, General James E. Cartwright, Commander of the U.S. Strategic Command, the DoD's leader charged with overseeing U.S. military global strategic planning, including nuclear deterrence and space operations, testified to the Strategic Forces Subcommittee of the Senate Armed Services Committee in Congress that U.S. national security, the economy, and the quality of our way of life "are all linked to our freedom of action in space." General Cartwright added that it is vitally important to "protect our space assets and our ability to operate freely in – and from – space."[8]

The Defense Science Board, Air Force Science Advisory Board, and Department of Defense leaders are not the only advocates of space and its significance to the nation's security. This claim is echoed by academics as well. The assertion that "…space has been and will continue to be important to our national security"[9] is supported by numerous authors and noted experts on space including: Barry Watts in *The Military Use of Space: A Diagnostic Assessment*; Steven Lambakis in *On the Edge of Earth: The Future of American Space Power*; Everett C. Dolman in *Astropolitik: Classical Geopolitics in the Space Age*; Bob Preston and his team in their RAND book *Space Weapons, Earth Wars*; and M.V. Smith in his article *Ten Propositions Regarding Space Power*. Some of the preceding authors also address the ongoing debate on whether to weaponize space or not. While this debate relates to issues of national security, it is a highly controversial topic and though vitally important, it will not be addressed in this paper. Ultimately, future wars will be fought in this newest domain and nations must be prepared to address the prospect.

While open warfare is currently not being fought in the highest frontier, it is being fought on land, in and on the sea, and in the air. Space systems such as the Global Positioning System (GPS), Satellite Communications (SATCOM), and Space-Based Infrared System (SBIRS) High, among others, aid the national security apparatus to navigate, communicate, conduct intelligence, and accomplish command and control. Because the nation's defense is reliant on these capabilities, current modes of land, air, sea, and cyber warfighting would be significantly constrained if the ability or access to use the space assets was either hindered or denied. The systems currently in space cost billions of dollars and have limited lifetimes. Furthermore, the technology onboard is outdated soon after the systems are launched and often prior to their deployment, particularly when it comes to the information-related systems on board.

The greatest challenges the U.S. faces in the acquisition and launch of additional advanced, hardened, and secure space assets are their massive cost coupled with their enormous weight, the ability to provide lift, to supply extended power, and to manage heat. For example, today it costs approximately $20,000 per pound to send a satellite into geosynchronous orbit and about $10,000 per pound to send the space shuttle into orbit.[10] Furthermore, at this point in time, any country or non-state actor with the money to do so can remove the functionality of U.S. spacecraft.[11] Dennis M. Bushnell, Chief Scientist at the National Aeronautics and Space Administration (NASA) Langley Research Center, agrees vehemently and argues that our nation's "space vulnerabilities are absolutely hideous."[12]

**Vulnerabilities.** The U.S. retains the strategic advantage in space today; however, nations around the world are gaining ground in space in various areas such as research and development, asset acquisition and deployment, and anti-satellite weapon employment. According to *The Joint Operating Environment 2008* document published by the U.S. Joint Forces Command, "Over the past several decades the U.S. has enjoyed unchallenged dominance over the dark realm beyond the atmosphere." This statement is true. However, defense experts also concur that the increasing proliferation of launch and satellite capabilities, as well as the development of anti-satellite capabilities, has begun to level the playing field. Other countries are leveraging the benefits of space for both commercial and military applications, and the U.S. already confronts increased competition for its use. Nothing better illustrates this point then the recent launch of a small satellite by Iran. This will increasingly be the case over the coming decades.[13] A review of commercial satellite use for public imagery consumption asserts that "(t)he number of sources for satellite imagery continues to grow, fueled not only by government customers in the USA and worldwide, but by an explosion of public usage."[14] The implications are clear: the Joint Force will have to be prepared to "defend the space-based systems on which so many of its capabilities depend."[15] Following an August 2008 visit to the U.S. Space Command, retired General Barry J. McCaffrey predicted that "the next Administration will have at most a year to analyze a series of difficult strategic and investment space decisions before U.S. global superiority will start rapidly eroding."[16]

Congress recently arrived at some of the same conclusions. A 2008 *House Report on Challenges and Recommendations for U.S. Overhead Architecture* deduced that "(t)he U.S. is losing its preeminence in space." In the report they wrote that there is a "narrowing gap between U.S. capabilities and emerging space powers such as Russia, India, and China." The report further added that

> "(s)pace continues to play an increasingly important role in supporting the national security interests of the U.S. As the number of threats increase, the nation must continue to deliver space capabilities that provide policy-makers and the war fighter with the information they need. The next few years are a defining moment for the U.S…decisive action is required to chart a successful course to preeminence in space."[17]

The problems to maintain preeminence and viability in space are complex and varied and alternative solutions must be found.

Space programs at the National Reconnaissance Office (NRO) and in the U.S. Air Force have been plagued with multi-billion dollar cost overruns and lengthy delays. Former Director of Central Intelligence (DCI) and current Secretary of Defense Robert Gates are concerned about the availability of services from space, especially when threats to the nation's space assets are growing. These threats include China's successful shoot down of one of its own satellites in 2007 and significant advances in directed-energy technology that can blind, disrupt, and destroy satellites. While serving as the DCI, Gates "advocated unsuccessfully for a mix of the large, multipurpose intelligence satellites and small, easily launched, single-purpose, limited-orbit-time capabilities that we could throw up with a number of different launchers."[18] The technological advances to accomplish Secretary Gates' proposal are closer than ever before but they require out-of-the-box thinking, a commitment to technological change, and willingness to expand research and development at a time we are fighting two land wars while battling forces of terrorism around the world.

One such out-of-the-box thinker is Ivan Bekey. In his book *Advanced Space System Concepts and Technologies: 2010-2030+* he contends that if we use "linear extrapolation with respect to space capability several decades into the future" the prospect for space will be "very gloomy."[19] Using this linear train of thought, he expects that the cost of launch will be close to what it is today; spacecrafts with the same function and performance will weigh about the same; spacecraft cost will continue to be tens of thousands of dollars per kilogram; power consumption will continue to be costly and limited; military spacecraft will continue similar roles and functions; and communications spacecraft will continue to be expensive with short life expectancies and quick obsolescence once launched.[20] These prospects will not afford the U.S. the capacity or ability to make significant advancements in space. Linear thought, coupled with the current and emerging global threats to U.S. space supremacy, have the potential to bring the nation to a critical juncture quickly in space, if the U.S. is not there already.

The U.S. may be at a critical juncture in the dominance of space. Following an August 2008 visit to Air Force Space Command, General Barry R. McCaffrey, USA (Retired), Adjunct Professor of International Relations, U.S. Military Academy, highlights the following in his After Action Report Bottom Line:

1. “The U.S. Air Force has owned the space domain for 50+ years with no serious threat to our dominance of the high frontier. That golden era has come to an end.

2. The control of space is central to all U.S. Joint Operational Forces and net-centric warfare. We lose 35 years of modernization if we lose space.

3. If U.S. orbital assets and control are put at jeopardy, then our joint ground-sea-air combat effectiveness is degraded by an order of magnitude.

4. This U.S. space dominance superiority gap is rapidly narrowing. Both nations and non-state actors have now obtained or are leasing space capabilities. (Russia, China, India, Japan, EU, Israel, Taiwan, Brazil, Argentina, Algeria, Morocco, Saudi Arabia, and others)

5. Several nations and non-state actors have created active, effective anti-satellite offensive warfare capabilities. (Alternative Options: kinetic impact weapons electronic jamming, laser heating or pulsed laser mechanical effects, chemical attack of orbital surfaces, ground attack against control sites, intense RF energy, nuclear direct attack with gamma rays and neutrons, attack with indirect nuclear effects above the atmosphere, intense beams of neutral particles.)

6. The Russians (April 1980), the U.S. (September 1985), and the Chinese (January 2007) have clearly demonstrated in the unclassified world a direct kinetic kill ASAT capability.

7. Space is getting more crowded and more dangerous. There are 450 active foreign spacecraft in orbit today. (300+ are COMSATs in geostationary orbit.) By 2010 there will be more than 600 foreign spacecraft. Satellites are now being launched from 12 known foreign launch sites as well as from sea launch locations.

8. Space is getting cheaper, smaller, and commercial.” [21]

General McCaffrey also came up with several key judgments during his visit about the near-term space environment. Those judgments are:

1. “The total number of foreign satellites in orbit and their capabilities will dramatically increase in the coming decade with both peer group competitor states and non-state actors posing a new and dangerous threat to US space dominance. The EU will have a commercially capability that will rival that of the US.

2. Adversaries to include criminal organizations and terrorist groups will acquire from third parties the capabilities to destroy, deny, and deceive US space systems.

3. Several countries, to include the current Russian and Chinese capability, will pose a direct kinetic threat to U.S. on-orbit assets.

4. Russia will become the dominant international leader in military space capabilities during the coming decade.

5. The U.S. will lose the ability to conduct covert military operations as we are denied concealment and deception by the wholesale proliferation of high-quality imagery and SIGINT satellites in the possession of our adversaries.

6. The capability to conduct electronic attack against our satellites will be a tool in the hands of terrorists and other non-state actors if we do not rapidly invest in new hardening and other defensive technology.

7. Terrorist and state actors will actively prepare to attack U.S. ground satellite control capabilities.

8. All international commercial, civil, military and government actors will become centrally and absolutely dependant on global high-quality satellite communications and GPS capabilities. This is an opportunity and a threat at the same moment."[22]

General McCaffrey finished with the assessment that "many of these conclusions are destabilizing to U.S. national security. Most of these rapidly emerging new realities can be mitigated or turned to our advantage by smart investments and newly invigorated national leadership and creativity." The U.S. is at a crossroad and it is imperative that leaders re-examine and restore the nation's commitment to space. General McCaffrey proposed that "it is time for a new assessment of the strategic risk we face and a renewed sense of energy to modernizing and changing the strategic posture of our global forces."[23]

Referring back to Bekey's assessment with respect to linear thinking, the nation ought to refrain from using this default way of thought and take an alternate approach to ensure the U.S. has the capacity and ability to make significant advancements in space. Basing predictions on past technological progress, futurists and scientists contend that humanity will witness exponential progress in the coming years. Assuming their calculations are correct a variety of options become possible. Our nation can seek to: drastically reduce the cost of launch from what it is today; dramatically improve the function and performance of spacecraft; significantly decrease the cost of power consumption and increase spacecraft longevity; expand the roles and functions of military, civil and private spacecraft; or decrease cost of communications spacecraft while expanding life expectancies and currency. Alternately the nation can seek to significantly reduce the cost of a spacecraft from the tens of thousands of dollars per kilogram it costs today for the function and performance the spacecraft currently provides. Or better yet, the nation can seek to exponentially improve the functions and performance of the spacecraft so that the spacecraft's capabilities far outweigh the cost. To accomplish this, the U.S. will need to capitalize on current scientific breakthroughs and disruptive technologies. Fortunately the rapidly advancing technologies that have the ability to transform and revolutionize virtually every industry to include space are literally on the horizon.

## Section Three

## Advancing Technologies—

## Genetics, Robotics, Information Technology, and Nanotechnology

There are numerous rapidly advancing, disruptive technologies that have the capacity to impact U.S. national security. However, the ones with the ability to truly transform and revolutionize our world as we know it today are genetics, robotics, information technology, and nanotechnology. These new technologies, coupled with the premise that the world is becoming flatter, are empowering individuals around the world to participate in globalization by figuratively shrinking the world to a minuscule size. Rapid globalization, or worldwide interdependence on steroids, has proliferated advancing technologies, flattened the world, and impacted its polarity.

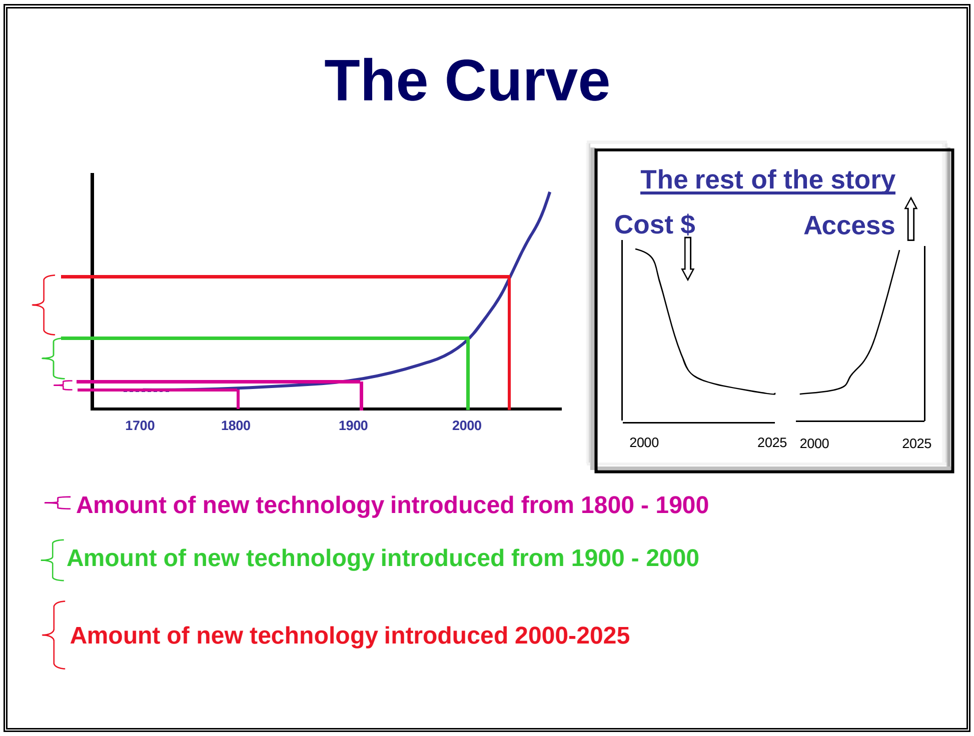
Thomas L. Friedman asserts that we are now in the third great era of Globalization. The first, Globalization 1.0, started in "1492—when Columbus set sail, opening trade between the Old World and the New—until around 1800…shrinking the world from a size large to a size medium." The dynamic force for global integration was the brawn, muscle, horsepower, wind power, or steam power a nation possessed. The second era, Globalization 2.0, started roughly around 1800 through 2000 and "shrank the world…to a size small." The dynamic force in 2.0 was multinational companies powered by falling transportation and telecommunication costs. Friedman argues that in 2000 we entered Globalization 3.0 which "shrank the world …to a size tiny and flattened the playing field at the same time." His central thesis is that the dynamic force for global integration is the power for individuals to collaborate and compete globally with the newest applications of software and the global fiber-optic network tying everyone together. The transformational piece of this era is that it is "shrinking and flattening the world…and empowering individuals" around the world in countries like India, China, Latin America, Russia, and the Middle East to participate in both the beneficial and harmful aspects of globalization.[24] The ongoing transformation ensures that high-tech research, development, and consumer products are made available to people in all parts of the world thus furthering technological advances even faster. This ongoing transformation is equally applicable to the space industry as nations around the world are entering the space domain by accessing widely available space-enabled services, establishing launch capabilities, and developing satellite manufacturing bases, among others. The current world financial crisis may slow this progress temporarily but the forces at work are simply too compelling to dramatically change the results.

Another futurist, Ray Kurzweil, contends that the first 50 years of this century "will be characterized by three overlapping revolutions—in Genetics, Nanotechnology, and Robotics" or GNR. He believes that we are already in the beginning stages of the Genetics revolution, that the Nanotechnology revolution "will enable us to redesign and rebuild—molecule by molecule—our bodies and brains and the world in which we interact," and that the most powerful impending revolution is the one in Robotics. [25] Kurzweil refers to the legendary information theorist John von Neumann's ideas that "human progress is exponential rather than linear" and that "exponential growth is seductive, starting out slowly and virtually unnoticeably, but beyond the knee of the curve it turns explosive and profoundly transformative." He contends that most long-range forecasts of what is feasible in the field of technology dramatically underestimate the power of future developments because they view history in a linear manner vice exponentially.

He argues that "we won't experience one hundred years of technological advance in the twenty-first century; we will witness on the order of twenty thousand years of progress…or about one thousand times greater than what was achieved in the twentieth century."[26] While Kurzweil cites information technology as a vital component of this revolution, another theorist incorporates information technology as one of the critical drivers.

Joel Garreau also explores this ongoing revolution and contends that four "intertwining technologies are cranking up…" They are the technologies for genetic, robotic, information, and nano processes or GRIN. He explains that these four advancing technologies "are intermingling and feeding on one another, and they are collectively creating a curve of change unlike anything we humans have ever seen."[27] This Curve of change will transform and revolutionize every field of technology, to include space technology.

The Curve indicates that the amount of new technology introduced in the 1800s was significantly smaller than the amount of technology introduced in the 1900s. Furthermore, the curve denotes that the amount of technology that is expected between 2000 and 2025 is significantly greater than what was achieved in the 1900s. The other part of the equation is that as the cost of technology is being driven down the access to the technology is being driven up allowing more and more people around the world the opportunity to use or exploit it. The following chart depicts the Curve.




[28] From a Mini Brief on Accelerating Change, Center for Strategy & Technology, Air University, 2008.

Another factor in the ongoing revolution is based on Moore's Law which still stands today. It states that the processing power per price of computers will increase by a factor of 1.5 every year. This is not expected to change or end in the next two decades.[29] Additionally, Garreau points out that every year the cost-performance ratio of internet services and modems is doubling, the Internet backbone bandwidth and the size of the Internet itself is doubling, and acceleration based on Moore's Law is proliferating. Because of this acceleration in information technology, other transformative technologies such as genetics, robotics, and nanotechnology are beginning to spawn and rapidly accelerate as well.[30] This also has a profound effect on virtually every technology, to include those technologies employed in the space domain.

Genetics, robotics, information technology, and nanotechnology are truly transformative technologies with the potential to impact U.S. national security both positively and negatively.

But of the four, nanotechnology, *the underlying technology that makes other things possible,* is the key to future space viability and dominance. So what is nanotechnology and why are nanotechnology-enabled space systems ideal for the space domain?

**Nanotechnology and Space Applications**. The origin of the word nanotechnology dates back to 1987 when K. Eric Drexler published *Engines of Creation: The Coming Era of Nanotechnology*; however, the concept itself emerged in the early 1970s.[31] But even before then, the famous scientist Richard Feynman foresaw the concept of nanotechnology in 1959 when he gave a now-celebrated talk "There's Plenty of Room at the Bottom" in which he saw the advantages of ultraminiturization in computer electronics.[32] His foresight of what nanotechnology has now evolved into was remarkable and a superb example of nonlinear thinking that is a guide to how future space systems need to be considered.

Nano is the Greek word for dwarf and technically equates to one billionth.[33] One nanometer (nm) is one-billionth of a meter or, in more easily understood terms, one nanometer is 10,000 times smaller than the width of a human hair. There are several different meanings to the concept of nanotechnology but two are most prevalent. The first "is a broad, stretched version meaning any technology dealing with something less than 100 nanometers in size." The second is closer to the original definition "designing and building machines in which every atom and chemical bond is specified precisely."[34] Put another way, nanotechnology is "specifically the technology we predict when the tide of technological progress washes against the shore of atomic physics (the quantum mechanics of electrons, with nuclei considered as unchangeable, primitive particles)." "Nanotechnology is not a set of particular techniques, devices, or products. It is, rather, the set of capabilities that we will have when our technology gets near the limits set by atomic physics."[35] In simplest terms, nanotechnology consists of: "research and technology development at the 1- to- 100nm size; creating and using structures that have novel properties because of their small size; and the ability to control or manipulate at the atomic scale."[36] Nanotechnology's appeal is that "unusual physical, chemical, and biological properties can emerge in materials at the nanoscale. These properties may differ in important ways from the properties of bulk materials and single atoms or molecules."[37] There are many consumer products already out in the market that have capitalized on nanotechnology.

Current widely available nanotechnology enabled products are faster computers, higher density memory devices, improved baseball bats, lighter weight auto parts, stain resistant clothing, cosmetics, and clear sunscreen.[38] These products are modest and evolutionary in nature. However, the best is yet to come. According to J. Storrs Hall in his book *Nanofuture: What's Next for Nanotechnology*, nanotechnology has the potential to lead the next industrial revolution.[39] A similar forecast is made by Michael Laine. He believes that the discovery of nanotubes will revolutionize this time in history. Nanotubes are "a world-changing technology. Every age has been defined by the material building blocks available…such as stone, bronze, iron. The next age might be defined as the carbon age."[40]

Nanotechnology is real, world-changing, and has had an effect on a wide variety of materials and processes, which have ideal properties and great potential for employment in space and significant implications for space viability and dominance. Some of the materials and processes with space applications include: nanoparticles (ultrafine powders); carbon nanotubes or buckytubes (strips of graphite rolled up into a cylinder, 40 to 60 times stronger than industrial steel); nanolithography (a process used to make electronic microchips); nanomanipulation (the ability to manipulate on the nanoscale which has been done in two dimensions for over a decade and scientists are now working toward third dimension); nanoelectronics (the most advanced capabilities that can be synthesized by self-assembly); nanomemories (the process of reading and writing data at molecular densities); nanobatteries; and the process of self-assembly ( atomically precise pieces sticking together using chemistry or molecular biology).[41]

Materials enabled by nanotechnology, or nanomaterials, are ideal for space and are "great candidates for spacecraft applications."[42] "In spacecraft high temperature resistance and material strength is critical since rocket engines, thrusters, and vectoring nozzles often work at much higher temperatures…Satellite life is mostly set by the amount of fuel they carry. In fact, more than a third of onboard fuel is spent by partial and inefficient fuel combustion. Combustion is poor because onboard igniters wear out fast and don't perform." [43] Nanotechnology-enabled space applications under development include:

1. Carbon nanotube materials: which are lightweight and will reduce the weight of satellites and spaceships while increasing the structural strength and can be used to build lightweight solar sails that "use the pressure of light from the sun reflecting on the mirror-like solar cell to propel a spacecraft."

2. Nanomaterial, like nannocrystalline tungsten-titanium dibordie-copper composite: which offer "a chance to increase igniter life and performance."[44]

3. Nanosensors: which will monitor "the levels of trace chemicals" in spacecraft for performance measurement and can be deployed in a network will be able to "search large areas of planets" for traces of water or other chemicals.

4. Infrared sensors: already widely used is space for satellite-based earth/atmosphere imaging research, satellite navigation tool, optical data communication, and astronomy instrument sighting, and will be improved upon by developments of a variety of nanostructures.[45]

5. Bio-nano robots in spacesuits: for integration into two layers of the suit. The outer layer could self-heal if punctured and the inner layer could monitor vital signs and provide medication in the case of an emergency.

6. Microelectromechanical systems (MEMS) devices: for use in thrusters for spacecraft and could be used for acceleration of "nanoparaticles "reduc[ing] the weight and complexity of thrusters…"[46]

7. Atomic Force microscope (AFM) based nanorobotic systems: for improved efficiency in manipulating nano-objects with "broad applications for nano imprinting, manipulating nano particles, DNA molecules, and assembling nano devices."[47]

8. Nanostructured optoelectronics: "offer space applications in optical satellite telecommunications and/or sensory technology (e.g., infrared sensors). Optical wireless data links are important for intra-satellite communication as well as optical inter-satellite links. Smaller and lighter devices having a higher bandwidth compared to common microwave communications are always needed."[48]

Nanotechnology enabled optical technology as described above is key to data relay processing such as providing high data rates with low mass, low power terminals, and secure, interference-free communications. One way and bidirectional optical links between satellites is already being successfully employed by the European Space Agency's Advanced Relay Technology Mission (ARTEMIS), among others.[49] So the secret is out. Nanotechnology enabled materials, processes, and applications can make a world of difference. So who is investing in this relatively new, revolutionary technology?

Many U.S. government, industry, and academic institutions are investing in the application of nanotechnology enabled materials, processes, and applications today such as the ones listed above. Back in 1998 an Interagency Working Group on nanotechnology was established in the U.S. The first government-sponsored nanotechnology program, the U.S. National Nanotechnology Initiative (NNI) was established two years later in 2000. The National Science, Engineering, and Technology Subcommittee was created under the National Science and Technology Council's Committee on Technology to coordinate efforts and, subsequently, the Nanotechnology Coordination Office was stood up to synchronize federal nanotechnology efforts. The 21st Century Nanotechnology Research and Development Act was enacted in 2003 which authorized appropriations for research and created the National Nanotechnology Advisory Panel calling for a review every three years by the National Research Council of the National Academies. The NNI Strategic Plan 2007, updated from the 2004 version, highlights the fact that NNI will receive reviews by the President's Council of Advisors on Science and Technology and the National Research Council.[50]

Each year the President proposed additional funding for nanotechnology and Congress has granted it. Since the NNI's creation, $8.4 billion has been appropriated for nanotechnology research and development to "foster continued U.S. technological leadership and to support the technology's development with long term goals of: creating high-wage jobs, economic growth, and wealth creation; addressing critical national needs; renewing U.S. manufacturing leadership; and improving health, the environment, and the overall quality of life."[51] While the goals are admirable, the $8.4 billion over a decade or so is not nearly enough.

The NNI involves 25 federal agencies and has four main goals which are listed in the Strategic Plan 2007, updated from the 2004 version. They are to: "advance a world-class research and development program; foster the transfer of new technologies into products for commercial and public benefit; develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology; and support responsible development of nanotechnology."[52] The NNI has eight program components: "fundamental nanoscale phenomena and processes; nanomaterials; nanoscale devices and systems; nanomanufacturing; instrumentation research, metrology, and standards; major research facilities and instrumentation acquisition; environment, health, and safety; and education and societal dimensions." Since 2006 the Department of Energy has established five new Nanoscale Research Centers "to support the synthesis, processing, fabrication, and analysis at the nanoscale…"[53] The DoD is listed as one of the primary collaborators on the first four components and a secondary collaborator on the remaining components.[54]

The U.S. government Defense Advanced Research Projects Agency (DARPA) is also a dominant player in sponsoring nanotechnology programs around the country. Its role is to maintain the technological superiority of the U.S. military and prevent technological surprise from harming national security through the funding of high-risk, high-reward research and development projects to include those having to do with space employment as well as nanotechnology-enabled projects.[55]

With respect to dual-use technologies for the defense industry, the Air Force, the Army, and Navy research laboratories have developed their own unique approaches such as establishing the Air Force Research Laboratory (AFRL) Nanotechnology Initiative, the Army Research Laboratory Nanoelectronics Laboratory, and the Naval Research laboratory Institute for Nanoscience. Work at AFRL and associated programs have "expanded the existing Air Force materials processing and characterization infrastructure" and have "accelerated the development of engineered nanoscale materials for morphing vehicles, alternative energy generation and storage concepts, and improved propellants" among other contributions.[56] Furthermore, the NNI notes that the power of nanotechnology has the "potential to transform and revolutionize multiple technologies and industry sectors, including aerospace…homeland security and national defense, energy,…(and) information technology…" among other technologies and industries. The DoD is listed as having a central role in all of the above "high-impact application opportunities" where critical research will significantly advance those applications. The DoD is also listed has owning a supporting role in all other application areas.[57]

However, according to the U.S. Joint Forces Command, "the present culture and bureaucratic structures of the DoD place major hurdles in the path of future innovation and adaptation."[58] If the U.S. DoD is unable to innovate and adapt the current scientific breakthroughs and disruptive technologies, then the military will be unable to capitalize on the rapidly advancing technologies that have the ability to transform and revolutionize U.S. armed forces, to include space forces. But other government agencies are beginning to see the vast potential of a future space domain enabled by nanotechnology.

In 2004 NASA was reportedly "spending more than $40 million a year on nanotechnology investigations."[59] The Center for Nanotechnology at NASA Ames is researching the application of nanotechnology "to reduce the mass, volume, and power consumption of a wide range of spacecraft systems including sensors, communications, navigation, and propulsion systems."[60] The Johnson Space Center Nano Materials Project is working on nanotube composites to reduce the weight of spacecrafts.[61]

A good deal of work is being done outside of the government as well. Arrowhead Research Corporation is a California-based company commercializing new technologies in the areas of life sciences, electronics, and energy. One of its subsidiaries, Unidym, Inc., is focused on the manufacture and application of carbon nanotubes in an effort to provide "carbon nanotube (CNT)-enabled products, bulk materials, and intellectual property to a wide range of customers and business partners."[62] Some of their products include various CNT materials, transparent conductive films, printable transistors, fuel cell electrodes, and solar cell development. Unidym bases their technology platform on four key technologies, high-purity, electronics grade CNTs, a network of CNTs allowing both flexible and rigid substrates, specialized technology processing, and platforms for component and device design.[63] With their 2007 merger with Carbon Nanotechnologies Inc., the company is considered a leader in "bringing carbon nanotube-based products to market."[64] The LiftPort Group and Elevator 2010 groups are working toward making a space elevator constructed of carbon nanotubes a reality.[65] The California NanoSystem Institute (CNSI) was established in 2000 through a California State initiative and opened a new state-of-the-art facility at the University of California Los Angeles (UCLA) in 2007. It is a unique research center whose mission is to "encourage university collaboration with industry and to enable the rapid commercialization of discoveries in nanosystems."[66]

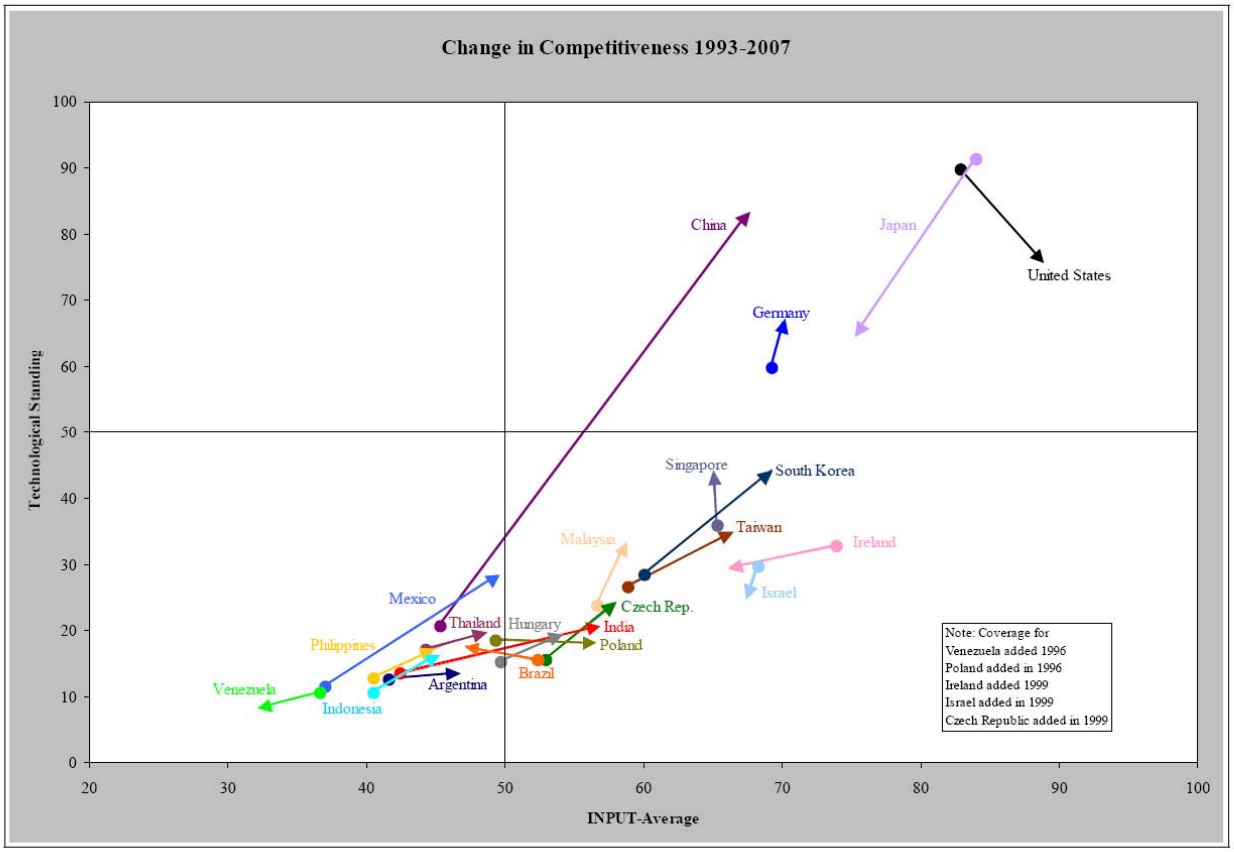
Many projects being worked at UCLA and in conjunction with other institutions are directly space related. For example, Professor Richard Wirz's project, satellite flying formations, is conceptually not out of bounds. Wirz explains that precision formations can provide observational aperture size much larger than those for single spacecraft, therefore allowing image resolution well beyond current capabilities. When combined with small and miniature spacecraft and propulsion technology, the precision formations should allow significant increases in spacecraft capabilities and survivability without additional launch requirements. If his project is fully funded it could be a reality in 10 years, if not funded then surely in 25 years. Wirz contends that the U.S. dominates space now but it is also the nation's Achilles heel.[67] Professor Yang Yang is working on polymer solar cells which "have shown potential to harness solar energy in a cost-effective way" and on the electronic properties of grapheme, which "make it a promising candidate for next-generation nanoelectronic devices" both of which can potentially be used in the future on satellites.[68] The Massachusetts Institute for technology (MIT) Space Nanotechnology Laboratory is “developing high performance instrumentation for use on spaceflights.”[69]

There are many more academic institutions and government agencies charging forward with this technology. But they are not only in the U.S. Numerous other nations now maintain and sustain advancing nanotechnology initiatives. U.S. leaders should be concerned.

**Global Competitors.** To date over 60 nations have established similar efforts to that of the U.S.' NNI. In 2006 the estimate for global investment in nanotechnology was around $12.4 billion with $6 billion of that supplied by the private sector. While the U.S. “appears to be the overall global leader” for now, the reality is that other countries are investing very heavily in research, development, and application in nanotechnologies based on the U.S. model and may already have the upper hand in specific areas.

Approximately 4,000 companies and research institutes are working on nanotechnology developments worldwide. Of those, 1,900 are in the services industry and over 1,000 companies are manufacturing products. The worldwide nanotechnology markets are projected to grow from $300 billion in 2006 to more than a trillion dollars in 2015.[70] As of 2007, the leading nations in nanotechnology development are the U.S., Japan, China, and Germany with China being one of the “world's leaders in terms of newly established nanotechnology firms.”[71] Russia just stood up their version of NNI and pledged over one billion dollars a year toward the initiative. The global requirement will be for two million skilled workers in the nanoscience and nanotechnology field worldwide with at least a third of those “needed in the U.S. to main global competitiveness.”[72]

Sixty-three percent of U.S. business leaders in the nanotechnology field believe that the U.S. is the world nanotechnology research, development and commercialization leader; however, they contend that the lead is narrowing.[73] Using purchasing power parity exchange rates, in 2006 the top ten nations investing public funding into nanotechnology research and development in priority order were the U.S., China, Japan, South Korea, Germany, France, Taiwan, the United Kingdom, India and Russia. The nation's leading private sector investments in 2006 were the U.S. and Japan, together accounting for nearly three-fourths of corporate investment.[74] While the U.S. led all other nations in scientific journal paper publication in 2005 with 24% of the world output, China was the only major competitor coming in second with 12% of the world's output. The U.S. dominance remains today but it also represents a decline from publishing 40% of the world's papers in the 1990s. The European Union led the U.S. in terms of quantitative analysis comparison of published papers but the European Union's share is in decline. China's share is rapidly increasing and is projected to surpass that of the U.S. if it has not already. The following chart indicates China's growth in competitiveness, which has now surpassed the U.S.' and Japan's, both of which are on the decline.




[75]Excerpt from a February 2008 Study by Georgia Tech released by the National Science Foundation

The nations with the highest commitment to nanotechnology were South Korea, China, and Japan with the European Union and the U.S. falling below world averages. A testament to the quality of research and development in the U.S., the papers from the U.S. were most frequently cited. Furthermore, the U.S. led in the area of patent grants.[76] According to the U.S. Patent and Trademark Office, more the 4,800 patents have been identified under the nanoclassification heading.[77] Statistics tell only a part of the story. The observations of space and nanotechnology experts are also important to assess. The ongoing research and development, travels, and joint publications of these professionals provide critical insight into the capabilities of the competitors as well as the potential of future nanotechnology-enabled space systems.

From the perspective of scientists and engineers at The Aerospace Corporation, a Federally-Funded Research and Development Center supporting the Space and Missile Systems Center, U.S. Space Command among other governmental organizations, the U.S. is currently leading the world in government funded nanotechnology research and development and is ahead in nanotechnology-enabled solar cells and structural materials. Dr. Donald A. Lewis, Principal Director of the Strategic Awareness and Policy Directorate (Project West Wing), and his team assess that Japan is a major player in research and development and is ahead of the U.S. in nanotechnology-enabled battery development.[78] China is working diligently and deliberately in nanotechnology focused research and development while Russia is not far behind. The European Union as an entity is also making significant strides.[79] Experts in academia provide important insights and observations as well.

According to Dr. Jim Health, an Elizabeth W. Gilloon Professor & Professor of Chemistry, Director of NanoSystems Biology Cancer Center at the California Institute of Technology and a Feynman Award Winner, the U.S. is in the lead with respect to nanotechnology research and development, however, the lead is not so clear anymore. Heath believes this is the case because the nation has been risk adverse in the past decade betting rather on sure things. He is certain that it is inevitable that nanotechnology enabled systems will be used in space. The biggest question is whether it will be by the U.S. or someone else.[80]

Dr. Gregory Carman, a Department of Mechanical and Aerospace Engineering Professor at UCLA, suspects China will overtake the U.S. in technology research in the near future. His observations come from his many visits to China and his contact with Chinese students in the

U.S. and Asia. Ten years ago Chinese students' desires were to stay in the U.S. but now that occurs far less. In the past China's equipment was rudimentary but during his last visit in 2007 he observed that they are now using state-of-the-art equipment. Furthermore, researchers in China now receive financial incentives to produce. Chinese publications and papers often duplicate the U.S.' but they are still quite good. He believes that in terms of technological research, the Chinese will surpass the U.S. in one to two decades.[81] The good news is that proponents in U.S. academic institutions and the private sector of nanotechnology's benefits are trying to do something about the nation's dwindling lead. This is a critical task and one that must be tackled if the U.S. will remain technologically competitive and, by extension, viable and dominant in space if space is to remain a viable domain.

Unidym executives also believe that the U.S. remains the leader in nanotechnology research and development for now and that their company holds the competitive edge in the nation by integrating various technologies. Unidym executives believe that, in addition to their regular foreign competitors such as China, Russia, and the European Union, the Middle East has become a competitor with Dubai investing vast amounts of money into nanotechnology. They cite that Korea is developing a "carbon valley" based on nanotechnology enabling materials which is similar to California's Silicon Valley. They assess that the gap between the U.S. and the rest of the world will narrow in 5 years with China leading shortly after that.[82]

Nanotechnology advocates in virtually all areas of the government, academia, and industry assert that this technology is bound to make "substantial contributions to national defense, homeland security, and space exploration and commercialization.[83] It will require a workforce that understands nanotechnology, electronics on the micro and nano scale, and the ins and the outs of the space industry. Why is the employment of nanotechnology in space application so critical?  Will China, Russia, or some other nation achieve space dominance?  Or will the U.S. be able to retain this critical strategic advantage?  A closer examination of what a nanotechnology-enabled future in space will look like is paramount.

## Section Four

## Space Tomorrow (2035)—Enabled by Nanotechnology

An ambitious, aggressive, and innovative plan backed by federal commitment of dollars and resources could afford the nation an opportunity to capitalize on the benefits of nanotechnology and allow the U.S. to retain its lead in nanotechnology. And with the application of nanotechnology-enabled space systems, the U.S. will have the ability to retain its dominance in space and concurrently sustain the viability of employing space-enabled technology in national defense.

**Near-Term Possibilities.** A great deal is possible in application of nanotechnology in space within the next 15 years. NASA predicts that the "scientific and technical revolution has just begun based upon the ability to systematically organize and manipulate matter at nanoscale." And that the "payoff is anticipated within the next 10-15 years." According to NASA,

1. "Advanced miniaturization is a key thrust to enable new science and exploration missions. Ultra small sensors, power sources, communication, navigation, and propulsion systems with very low mass, volume, and power consumption needed

2. Revolutions in electronics and computing will allow reconfigurable, autonomous, "thinking" spacecraft

3. Nanotechnology presents a whole new spectrum of opportunities to build device components and systems for entirely new space architectures. Networks of ultra small probes on planetary surfaces. Micro-rovers that drive, hops, fly, and burrow. Collection of microspacecraft making a variety of measurements."[84]

In a December 2008 presentation to the defense industry NASA scientists further concluded that

> "Nanotechnology can have a significant impact on materials for aerospace applications by enhancing durability, improving properties, [and] enabling multifunctionality. Applications of nanostructured materials can enable significant reductions in vehicle weight – fuels and emissions, improvements in safety and durability, [and] enhancements in performance."[85]

Another initiative is the creation of The National High Reliability Electronics Virtual Center (NHREVC). This is a Web-enabled Virtual Center for use by multiple organizations and sites from government, industry and academia across the nation to address the multidisciplinary challenge of electronics lifetime assessment. The Center's initial focus is on electron devices with active element sizes smaller than 100 nanometers specifically pre-qualification risk reduction of the emerging technologies. The motivation for the Center is rooted in a widely-held belief that "the DoD and intelligence community must actively adopt emerging electronics" because "obsolescence is driving us to new technologies…" and "hi-speed, low power consumption parts promise a major competitive advantage over our adversaries." The NHREVC's participants include The Aerospace Corporation, The Air Force Research Laboratory, universities, commercial industries, Office of Naval Research, government labs, Federally-Funded Research and Development Centers, and others with expansion to include more participants in Fiscal Year 2009 and beyond. They base their direction and focus on technology insertion roadmaps of the National Security Space, Missile Defense Agency, and NASA.[86]

A report on *Nanotechnology and U.S. Competitiveness* from The Congressional Research Service predicts that within the next five to ten years evolutionary changes based on nanotechnology will occur in the fields of medicine, protective clothing, energy, water purification, higher-density memory devices, agriculture production, environment protection and remediation. [87] These changes will also occurring in the space industry. In 2006 participants at the CANEUS Conference concluded that "nearly every space program worldwide has found remarkable and successful roles for micro and nano technologies (MNTs)" such as the creating of lighter weight, smaller-sized, less-power-dissipated, lower-cost materials for outer-space, aerospace, and military applications.[88] DARPA is working on a "concept of fractionated spacecraft, where a traditional monolithic satellite is replaced with a cluster of wirelessly interacting modules that deliver comparable mission capabilities and dramatically enhanced flexibility and robustness."[89]

Concrete advances are being made around the world as well. Surrey Space Center at the University of Surrey, United Kingdom CMOS, has already moved in this direction and invented SpaceChips as the foundation for a single-chip satellite, which will include "imaging, a solar cell, antennas, a digital radio, a CPU, and power control circuitry on a die that measures just 18 by 20 mm."[90] EADS' Astrium Ltd. Division has developed Micropacks for Space Microsystem Technologies (MST) which will be used to create suites of MST [commercial of the shelf] COTS sensors for assembly and integration "into 3D modular multilayer ceramic package[s]."[91] The benefit will be "the easy inclusion of additional sensors, hardware like MEMS gyros, scientific instruments, and advanced micropower and data-communications networking techniques, as well as a microcomputer on a chip…MEMS devices figured heavily in spacecraft propulsion, thrust and rocket designs of all types."[92] Many more nanotechnology-enabled probabilities and possibilities are on the horizon.

Peter Pesti compiled a comprehensive document titled *Roadmap of the 21st Century* that consists of Goldman Sachs, PricewaterhouseCoopers, the United Nations, and U.S. Intelligence Community reports; DoD roadmaps, a nanotechnology expert survey, and a semiconductor roadmap; and predictions by scientists, authors, and futurists. The list includes quite a number of nanotechnology relevant forecasts with space applications. The near-term possibilities with space applications are listed below and will be available:[93]

- By 2010:
  - NRAM (nanotube ram, always-on high density computer memory)
  - Smart and adaptable surfaces at the nanoscale as building block for Biodetection
  - Quantum dots: nanosized imaging agents for analysis/diagnosis inside cells
- By 2015:
  - Commercially available array of nanotubes: Biosensors for detection of single molecules based on nano arrays
  - Existing materials such as polymers replaced by nanostructured biomaterials
  - Sensory augmentation using sensory implants, nanoparticles
  - Targeted drug delivery based on nanoparticles
  - Optical tweezers: nanotools for manipulation inside cells
  - Commercially manufactured nanoelectronics chips using DNA or peptides
  - Nanotools and parts created by DNA
  - Nanowalkers, nanoworms, nanofish

**Longer-Term Predictions.** The *Roadmap of the 21st Century* nanotechnology relevant predictions with space applications envisioned in the longer-term beyond 2035 are listed below and will be available:[94]

- By 2025:
  - Nano-enabled space vehicles with 10 to 1000 times better performance than today
  - Nanofactories creating space vehicles with
    - Ion drives with 750k We/kg specific power
    - Speed 0.5 AU per day
    - 9.8 m/s2 accelerations
  - Ability to go from Earth to Mars in 1 to 3 days, Earth to Saturn in 20 days
  - Inexpensive carbon nanotube fiber with over 50GPatensile strength
  - Nanoengineered machines applied to manufacturing and process-control applications
  - Sensory augmentation using sensory implants, nanoparticles, etc.
  - Actuated diamond tools and Nanoparts created
  - Nanobiotechnology: Fundamental processes of the cellular cycle understood
  - Biological energy conversion systems used in artificial micro/nano systems
  - Nanotech based organism colonies
  - Introductory nanofactory
  - Nano-machine for theranostics (therapy and diagnostics) used inside body
  - Everything monitored and tracked by nano-RFID tags with build-in memory
  - Billion CPU personal nanocomputers
- By 2035:
  - First orbital country in space, nanotube structure many km in diameter at L5, population 100,000+
  - Nanotechnology plants created
  - Human cells interfaced with nanotech
  - Nanobots scan the brain from inside
  - Full immersion virtual reality with nanobots, from within the nervous system
  - Nanotechnology weapons used in war, over 500 million dead
- And beyond 2035:
  - Space elevator based on carbon nanotube built
  - Nanotech based virus communicable between machines and people, sent over the Internet
  - Real toy soldiers using nanotechnology
  - Nanobots swam projections used to create visual-auditory-tactile projections of people and objects in real reality
  - Nanoproduced food will ensure availability of food no longer affected by limited resources, bad crop weather, or spoilage

To make these near-term possibilities and longer-term prediction a reality, innovation, out-of-the-box thinking, and a focus on the exponential possibilities is a must. Ivan Bekey, author of *Advanced Space System Concepts and Technologies: 2010-2030+*, believes that "disruptive innovation" vice incremental improvements will revolutionize the changes in space.[95] He contends that the highest leverage technologies should be developed to make this occur. They are:

- "Adaptive piezoelectric reflectors membranes, actuated by electron beams
- Coherent cooperating distributed or swarmed spacecraft of all sizes
- Buckytube matrixless and composite structures and spacecraft components
- Long lightweight, high strength long-life tethers, wire and nonconducting
- MEMS FEEP integrated micropropultion assemblies
- Formation flying techniques with submillimeter relative position accuracies
- Spectrally split, multiple matched bandgap cells in concentrated solar power arrays
- Liquid crystal spatial light modulators with more than 1 mm of time delay correction
- Micro-particle stream heat radiators
- High capacity information transmission, processing, and storage to meet all needs"[96]

Bekey further speculates that "…the introduction of Buckytubes materials," into the manufacture of both spacecraft and launch vehicles, "could result in total weight and cost reductions of factors of 100,000 or more from today's levels." "Weight, which is today the major determinant of space system cost, will become essentially immaterial in the future."[97]

Bekey is absolutely right when he states "we must be willing to think unconventionally, big, far term, and high risk" by investing in disruptive technologies so that "space will become just another place." This will create a "whole new ballgame for defense space" as well as for commercial space. In terms of defense and space, he predicts that in the future:

- “Global force projection from space will be ubiquitous and devastatingly effective
- Complete situational awareness will exist from GEO at theater to global scales
- Many crews will be removed from harm’s way by performing functions from CONUS
- Precision weapons will be delivered globally from CONUS
- The size of, and need for, logistic tails to support operations costs will be greatly reduced
- Space radar will mostly replace AWACS, JSTARS, SAR and SPACETRACK
- Spacecraft development, deployment, and operations costs will approach those of aircraft
- Some space systems will be incrementally funded, emplaced, and upgraded
- Most of the advanced ideas of SAB’s ‘New World Vistas’ will be fielded.

BUT

- The U.S. will not have decisive technological advantages over others
- Commercial infrastructure and services will dominate space activity
- Congress will insist that DoD use these capabilities
- We will have to learn to observe, fight, and win in this environment.”[98]

Other space and nanotechnology experts make similar assertions that nanotechnology will enable radical changes in the space industry. Allan Rogers predicts that NASA spaceprobes will weigh 10 kg or less down from the current weight of hundreds of kilograms, soon to be down to 100 kg.[99] In a paper presented at the Fourth Foresight Conference on Molecular Nanotechnology, Thomas Lawrence McKendree studied “chemical rockets for putting payloads into Earth orbit, single and two stage architectures, synchronous and rotating skyhooks, solar sails, and solar electric ion engines, and large inhabited space colonies.” He calculated “how well those systems would perform when simply using micro and nanotechnology (MNT) technical performance parameters.” He concluded that “In *all* cases, MNT offers the possibility of significant system improvements.”[100]

Another potential application others are working on is the development of a space elevator mentioned previously. Bradley Edwards, President of Caron Designs, Inc., predicts that the space elevator will be built using carbon nanotubes (CNTs) and will allow quick space entry.

He added that "the same material could reduce the mass required for the lifting equipment on a space elevator, and also lighten solar power satellites and space stations." [101] These and other nanotechnology-enabled space applications are limited only by imagination, innovation, ability and dedication to overcome the challenges.

**Addressing the Challenges**. What will U.S. defense capabilities be in 20 to 25 years from now in this radically different environment? What should the DoD, or more precisely the Air Force do now to address those potential challenges? One answer is wargaming. The U.S. Air Force Future Capabilities Game 2007 is a wargame designed to "shape military capabilities to best respond to emerging future warfighting environments and national security challenges." These wargames are used to "explore new concepts and capabilities and help prevent technological, strategic, and/or operational surprise." The report identified trends and shocks that are likely to erode traditional military advantages. The primary drivers include the following predictions: "a flattening technology gap will reduce U.S. military advantage…computing capability will greatly enhance cyberspace capabilities…(and) rising energy and U.S. manpower costs will force the U.S. military toward energy-efficient and automated systems."[102] The Wargame predicted that the following long-term challenges to capabilities are likely: "Deteriorating space security…growing anti-access (land, sea, and air) capabilities…increasing number of weapons of mass destruction by more nations…a rapidly growing information-based global society…(and) the blurring of lines between major combat operations and irregular warfare…"[103] Because the undertaking is so difficult, of the five long-term challenges predicted by the Wargame, the U.S. has placed insufficient emphasis on and action toward addressing the deterioration of space security and expanded capability. Nanotechnology may hold the key to overcoming the challenges.

The next step is to study accelerating technologies, forecast their impact in the future on the military, and determine what leaders should do today to address the encroaching challenges. The Air Force's Blue Horizons Program is a Headquarters sponsored long range planning effort lead by exemplary faculty members and comprised of volunteer Air War College and Air Command and Staff College line officers within the top 12 percent of their peer group. The research program is designed to mesh with the Quadrennial Defense Cycle. The program focuses on how accelerating technological change interacts with a shifting strategic landscape to produce massive dynamic change. This change then acts as a catalyst to create a very disturbing disruptive threat to the U.S. and a serious challenge to the Air Force's future dominance. The 2007-08 Blue Horizons Program studied nanotechnology, biotechnology, directed energy, and cyber through 2030 and rooted its findings in a quantitative analysis methodology.

Of the multiple 2007-08 Blue Horizons findings, the conclusions on nanotechnology held that nanotechnology is the easily forgotten game changer. Furthermore, nanotechnology is now being added to make systems better and it will become a stand-alone system in 2030. The team also came up with four alternate futures for 2030 represented by a Peer China, a Resurgent Russia, a Failed State, and a Jihadist Insurgency scenario. These alternate futures provide a plausible tool to understand future challenges and logical extrapolations based on extensive research. The current 2008-09 program specific task is to "develop a prioritized list of concepts and their key enabling technologies that the U.S. Air Force will need to maintain the dominant air, space, and cyber forces in the future."

Based on the previous research presented in this paper and borrowing heavily from Bekey's implications, the following five assumptions are offered about what nanotechnology-enabled space capabilities could provide the U.S. 20 to 25 years from today. First, the U.S. will employ satellites that possess the capability to perform up to 1,000 times better than the satellites deployed today. Second, the U.S. military will possess the option of global force projection from the domain of space. Third, the U.S. will possess the capability to achieve and maintain complete situational awareness in CONUS for assets located in space. Fourth, the U.S. will have the capacity to execute the majority of its warfighting capabilities from CONUS using space-enabled technology. Fifth, the U.S. will have the ability to deliver precision weaponry from CONUS via assets in space. Because the capabilities listed in the third, fourth, and fifth assumptions will be primarily space-based, they will be in the hands of the warfighter either in the CONUS, on the battlefield, or alternately anywhere the warfighter requires access to those capabilities.

Applying the promise of nanotechnology-enabled space capabilities to the 2007-08 Blue Horizons Alternate Futures work provides interesting implications for the U.S. 20 to 25 years from now. The following provides a brief glimpse into what the future may hold with a Peer China, Resurgent Russia, Failed State, and a Jihadist Insurgency.

In the case of a future Peer China scenario, Beijing possesses a greater Gross Domestic Product than the U.S, its success in exporting high technology product likely continues to dominate the world,[104] and its global competitiveness far surpasses all other nations to include the European Union. In the case of a future Resurgent Russia, Moscow becomes a key supplier of world energy, the nation grows into a major world economic player as a result of its rapid wealth from hydrocarbon exports, and its autocratic and corrupt leaders demand and seek a role on the world stage.

In the Peer China and Resurgent Russia scenarios, both nations are likely to have attained significant wealth, possess the resources and capabilities to further refine the employment of nanotechnology-enabled space systems, and continue to possess the desire to attain or retain space dominance or supremacy at all costs. The implications are that if both China and Russia dominate space and the U.S. does not, the U.S. would become dependent upon either or both of these two nations for land, sea, air, and cyber defense capabilities as well as other commercial and private services such as television broadcasting, telephone services, commercial aviation and shipping, train transportation, police and fire emergency services, personal vehicle navigation, finance and banking, product tracking, and agriculture. Consequently, the U.S. would benefit by aggressively developing nanotechnology-enabled space systems today as China and Russia are likely to also develop these systems in an effort to dominate the high frontier in the future.

In the case a future Failed State Scenario using Nigeria as a Case Study, Nigeria continues to maintain the largest population in Africa with a growing Islamic population in the North following Shari's Law, institutional corruption is rampant throughout, the nation is a haven for transnational criminal enterprises, and the state's failure could ignite wars between and within neighboring countries. In the case of a future Jihadist Insurgency Scenario using Saudi Arabia as a Case Study, the vital oil resources and military are taken over by the Jihadists, fear over Muslim holy cities falling into the hands of radical Muslims is heightened, the increasing population growth coupled with a poor economic outlook is fostering discontent, and low level insurgency provides for a strong potential for expanded religious, ethnic, and tribal conflict within the state and region.

In closer examination of these two cases, it is not likely that Nigeria or Saudi Arabia will possess nanotechnology-enabled space systems but they will be the users of such systems. However, the likelihood exists that rogue non-state actors or terrorists being harbored in these two states would certainly have the potential to access these capabilities. And, as a result, the rogue non-state actors or terrorists would have the capacity to endanger the viability of the U.S. space force and thereby challenge U.S. national security. In these two scenarios the U.S. would benefit by aggressively developing nanotechnology-enabled space systems today to greatly enhance its future space capabilities and have the ability to project force globally via space. Furthermore, the U.S. would benefit by having the ability to gain the intelligence edge with complete situational awareness and by being able to execute a vast array of warfighting capabilities with true precision weaponry from anywhere in the CONUS or elsewhere using space assets while limiting the placement of troops in harm's way.

In any of the four scenarios the U.S. would benefit greatly if the nation would capitalize on, leverage, and develop nanotechnology-enabled space systems in an effort to ensure the viability of space and maintain dominant space forces in the future. One approach is to seek ways to exponentially improve the functions and performance of spacecrafts so that the spacecrafts' capabilities far outweigh the costs. Current advances in the research and development of nanotechnology and nanomaterials are already poised to make this happen. And this will probably happen very soon.

# Section Five

# Conclusion

It is hard to imagine life in the U.S. without the daily conveniences enabled by space, which have become routine and mundane to most. It is even more difficult to envision the nation's defense capabilities without the advantages of space. If we lose control of space, we risk losing command of U.S. forces, control of net-centric warfare, and 35 years of modernization of U.S. armed forces.[105] The nation must continue to deliver space capabilities that provide warfighters and policy-makers with the vital information, intelligence, and capabilities they need. According to the Defense Science Board and the Air Force Science Advisory Board, there is no viable alternative to the unique capabilities that space systems provide.[106] But threats to U.S. national security are increasing and will never cease.

In addition to demonstrated, direct kinetic kill anti-satellite capabilities, several nations and non-state actors have created or are working on active, effective anti-satellite offensive warfare capabilities such as kinetic impact weapons electronic jamming; laser heating or pulsed laser mechanical effects; chemical attack of orbital surfaces; ground attack against control sites; intense radio frequency energy; nuclear direct attack with gamma rays and neutrons; attack with indirect nuclear effects above the atmosphere; and intense beams of neutral particles, to name a few. The challenges are many and they are real.

The greatest challenges the U.S. faces today in the acquisition and launch of additional advanced, hardened, and secure space assets are their massive cost coupled with their enormous weight, the ability to provide lift, to supply extended power, and to manage heat. The potential solutions are numerous and varied. However, the U.S. must employ innovative, out-of-the-box thinking, renew its commitment to the advanced research and development of disruptive technologies such as nanotechnology, and restore its commitment to dominance in space in order to resolve the challenges.

Nanotechnology is real, world-changing, and has had an effect on a wide variety of materials and processes, which have ideal properties and great potential for employment in space. Nanotechnology is the underlying driving force in the expansion of space viability and dominance. Some of the nanotechnology materials and processes with space applications include: nanoparticles; carbon nanotubes (CNTs) or buckytubes; nanosensors; infrared sensors; nanolithography; nanoelectronics; microelectromechanical systems (MEMS) devices; nanomemories at molecular densities; nanobatteries; bio-nano robots; Atomic Force microscope (AFM)-based nanorobotic systems; nanostructured optoelectronics; two dimensional nanomanipulation with three dimensional nanomanipulation on the horizon; and the process of self-assembly. Furthermore, the employment of nanomaterials such as CNTs or buckytubes in launch and spacecraft materials have the potential to dramatically reduce the total weight and cost by factors of up to 100,000.[107] Nanotechnology can make a world of difference.

The payoffs in space will be expansive and huge in next 10 to 15 years. Nanotechnology-enabled spacecrafts and systems will possess significantly enhanced flexibility, robustness, safety, durability, and performance capabilities while experiencing concurrent reductions in costs. They will include ultra small sensors, power sources, communication and navigation, and propulsion systems. The payoffs will deliver dramatically reduced emissions, mass, volume, heat, and power and fuel consumption. They will include single chip satellites with multifunctionality and easily reconfigurable, modular, autonomous, thinking spacecraft able to assess and react to the environment. In the longer-term, the nanotechnology-enabled systems will likely provide self-assembled spacecrafts; space systems with 1,000 times the performance of today's systems; weapon systems enabled by nanotechnology; and carbon nanotube (CNT) space elevators; among others. The properties of nanotechnology-enabled materials and systems are ideal for space. Nanotechnology will be routinely employed in space. Which nation, federation or conglomeration of nations, corporation, academic institution, or team will be the first to capitalize on this technological revolution?

Since the inauguration January 2009, the new Administration has yet to address the importance of space to U.S. national security. However, prior to the November 2008 presidential election, then President-elect Barak Obama, responded to the top 14 science questions facing America. Three of those twelve questions were on the topics of space, national security, and innovation. With respect to space, President Obama pledged to reestablish the National Aeronautics and Space Council to oversee and coordinate civilian, military, commercial, and national security space activities and work toward a 21st Century vision of space that constantly pushes the envelope on new technologies. On the topic of national security, President Obama promised to ensure that our defense, homeland security, and intelligence agencies have the strong research leadership needed to revitalize U.S. defense research activities and achieve breakthrough science that can be quickly converted into new capabilities for U.S. security to include renewing DARPA. With respect to innovation, President Obama vowed to increase support for high-risk, high-payoff research portfolios at the nation's science agencies and invest in the breakthrough research to transform defense programs.[108] The general direction of the response was correct. Now major the muscle must be put behind it. The U.S. must take decisive action before the nation's security posture is irrevocably weakened.

The U.S. would benefit greatly if the nation would capitalize on, leverage, and develop nanotechnology-enabled space systems in an effort to ensure the viability of space and maintain dominant space forces in the future. Aggressive development of nanotechnology-enabled space systems by the U.S. today has the potential to facilitate future space viability and dominance in 2035 and beyond. Space is no longer the *final* frontier. Space is the frontier of the *future*.[109]

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of new scientific breakthroughs published in peer reviewed journals. The X axis, therefore, shows the current scientific position of the state; the Y-axis shows where the new research is being published – which is historically where scientific standing is derived. Of concern as we look to the future with China is that as new research in the U.S. is declining, it is rising within China at a phenomenal pace, allowing technological innovation within China to move forward at a rate faster than that of any other nation on the planet. China is already assessed as having passed the U.S. in overall scientific innovation in the field of nano-technology. If the trends across the remaining scientific disciplines were to remain unchanged, China would pass the U.S. in innovation and scientific standing in many, if not most, scientific fields within this study's timeframe."

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