Written Statement of
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Subcommittee on Space and Aeronautics
Science and Technology Committee
U.S. House of Representatives

Strengthening NASA's Technology Development Programs
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Madame Chairwoman, Ranking Member Olson and members of the Subcommittee, thank you for the honor of appearing before you today to discuss approaches to strengthen NASA's advanced concept and technology development programs. My name is Robert D. Braun. The views I express today have been shaped through a twenty-two year aerospace engineering career in government and academia. For sixteen years, I served on the technical staff of the NASA Langley Research Center. At NASA, I developed advanced space exploration concepts, managed multiple technology development efforts, and contributed to the design, development, test and operation of several robotic Mars flight systems. For the past six years, I have served on the faculty of the Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. As Director of Georgia Tech's Space Systems Design Laboratory, I lead an active research and educational program focused on the design of advanced flight systems and technologies for planetary exploration. The advanced space systems concept and technology maturation skills being developed by the undergraduate and graduate students at Georgia Tech are of significant interest to NASA, the U.S. Air Force, DARPA, our national labs, industry, and others in academia. It gives me great pride to work closely with these students, who are on their way to becoming the space systems engineers of our nation's future.

Today, I speak to you as the Co-chair of the National Research Council's Committee to Review the NASA Institute for Advanced Concepts, which recently released our report *Fostering Visions for the Future: A Review of the NASA Institute for Advanced Concepts*. The committee's twelve members were chosen by the NRC for their experience with advanced space and aeronautical concepts and their insight into cogent approaches to spark scientific innovation and creativity. They represent a diverse cross-section of aerospace sector experience, including NASA, DARPA, the SETI Institute, industry, and academia. The committee was co-chaired by Dianne S. Wiley, a Technical Fellow at Boeing Phantom Works and myself. I must say that it was a pleasure to work through the NRC with this talented and experienced group of people.

In response to the first question posed by the subcommittee, I would like to begin by summarizing our committee report.

## Fostering Visions of the Future: A Review of the NASA Institute for Advanced Concepts

NASA established the NASA Institute for Advanced Concepts (NIAC) in 1998 to provide an independent, open forum for the external analysis and definition of revolutionary space and aeronautics concepts to complement the advanced concepts activities conducted within the Agency. Funded at approximately $4 million per year (roughly 0.02% of NASA's budget), NIAC received a total of $36.2 million in NASA funding during the 9 years of its existence. As directed by the NASA SOW, NIAC focused on revolutionary advanced concept studies that could impact a NASA mission 10 to 40 years in the future. NIAC inspired an atmosphere of innovation that stretched the imagination and encouraged creativity. In response to its yearly solicitations, NIAC received a total of 1309 proposals, and made 126 Phase I awards and 42 Phase II awards, primarily to small businesses and universities, but also to large businesses and national laboratories. To reduce costs and maximize public accessibility, NIAC utilized an open, web-based environment to conduct solicitations, perform peer review, administer grant awards, and publicize its activities. NIAC received an “Excellent” performance rating in each NASA annual review held. Many NIAC grantees went on to receive additional funding for continued development of their concept from NASA, other government agencies or private industry. In addition to developing revolutionary concepts, NIAC placed an emphasis on science and engineering education as well as public outreach. At its inception, NIAC was envisioned as a crosscutting program reporting to the Agency’s Chief Technologist. In 2004, when the NASA Office of Aerospace Technology was dissolved, NIAC program management was transferred into the NASA Exploration Systems Mission Directorate. In 2007, NIAC was terminated.

In 2008, Congress directed the National Research Council (NRC) to conduct a review of the effectiveness of NIAC and to make recommendations concerning the importance of such a program to NASA and to the nation. Our committee was given the following statement of task:

1) Evaluate NIAC’s effectiveness in meeting its mission.
2) Evaluate the method by which grantees were selected.
3) Make recommendations on whether NIAC or a successor entity should be funded by the Federal government.
4) Make recommendations as to how the Federal Government in general and NASA in particular should solicit and infuse advanced concepts into its future systems.

In evaluating NIAC’s performance, the committee addressed the following questions:

1) To what extent were the NIAC-sponsored advanced concept studies innovative and technically competent?
2) How effective was NIAC in infusing advanced concepts into NASA’s strategic vision, future mission plans, and technology development programs?
3) How relevant were these studies to the aerospace sector at large?
4) How well did NIAC leverage potential partnerships or cost-sharing arrangements?
5) What potential approaches could NASA pursue in the future to generate advanced concepts either internally or from external sources of innovation?

The key findings and recommendations from our report can be summarized in the following seven statements:

**1) NIAC met its mission and accomplished its stated goals.** The committee found that NIAC’s approach to implementing its functions successfully met NASA-defined objectives, resulted in a cost-effective and timely execution of advanced concept studies, afforded an opportunity for external input of new ideas to the agency, and subsequently provided broad public exposure of NASA programs. NIAC was successful in encouraging and supporting a wide community of innovators from diverse disciplines and institutions as evidenced by receipt of 1309 proposals in its 9-year lifetime. The 126 NIAC Phase I studies were led by a total of 109 distinct principal investigators, each of whom led a research team of 3-10 personnel, often across multiple organizations. The majority of the NIAC-supported efforts were highly innovative. Many were successful in pushing the state of the art. Overall, the efforts supported produced results commensurate with the funding and risk involved.

**2) NIAC had infusion successes and challenges.** One important NIAC performance metric defined in the NASA SOW was achievement of 5 to 10 percent infusion of NIAC-developed Phase II concepts into NASA’s long-term plans. One way to gauge such infusion is to look at the receipt of post-NIAC funding for the continued development of a NIAC-funded concept. The committee found that 14 NIAC Phase I and Phase II projects, which were awarded $7 million by NIAC, received an additional $23.8 million in funding from a wide range of organizations, demonstrating the significance of the nation's investment in these NIAC advanced concepts. NIAC matured 12 of the 42 Phase II advanced concepts (29 percent), as measured by receipt of post-NIAC funding. In fact, 9 of these (21 percent) received post-NIAC funding from NASA itself. Over the long term, the ultimate criterion for NIAC success is the number of funded projects that make their way into the relevant NASA mission directorate decadal survey, strategic plan, or mission stream. The committee found that three NIAC Phase II efforts (7 percent of the Phase II awards) appear to have impacted NASA's long-term plans. Of significance, two of these efforts have either already been incorporated or are currently under consideration by the NRC Astronomy and Astrophysics Decadal Survey as future NASA missions: the MAXIM x-ray interferometry concept for black hole imaging and the New Worlds Observer constellation for exoplanet discovery. Considering the 40-year planning horizon of NIAC activities coupled with the 9-year existence of NIAC, the committee believes it is likely that the number of NIAC Phase II projects considered for NASA missions will continue to increase over time.

On the other hand, by design, the maturity of NIAC Phase II products was such that a substantial additional infusion of resources was needed before these advanced concepts could be deemed technically viable for implementation as part of a future NASA mission or flight program. The committee found that this technology readiness immaturity created infusion difficulties for the NIAC program and innovators, causing promising ideas to wither on the vine.

**3) NASA and the nation need a NIAC-like organization.** NASA is now an agency largely oriented toward flight-system development and operations. Priorities have thus diminished within NASA for long-range research and development efforts. At present, there is no NASA organization responsible for solicitation, evaluation, and maturation of advanced concepts (defined as those at technology readiness level one or two) or responsible for subsequent infusion of worthy concepts into NASA planning and development activities. Over the past few years, such NASA efforts have been ad hoc, lacking in long-term stability, and not integrated into the agency's strategic planning process. Managed in this fashion, advanced concept efforts will rarely produce mature products and the agency is at risk of driving away many of its most creative personnel. Our committee believes that NASA and the nation would be well served by maintaining a mechanism to investigate visionary, far-reaching advanced concepts as part of NASA's mission.[1] Concepts deemed feasible could be used to inform NASA's strategic planning process. Long-term, these concepts and technologies offer the potential for dramatic improvements in performance and/or cost of future aeronautical and space systems. As such, the committee recommends that NASA should reestablish a NIAC-like entity, referred to in our report as NIAC2, to seek out visionary, far-reaching, advanced concepts with the potential of significant benefit to accomplishing NASA's charter and to begin the process of maturing these advanced concepts for infusion into NASA's missions. The existence of such an organization would also demonstrate that NASA continues to be a driver of innovation and technological competitiveness, potentially serving as a critical element of NASA's public and educational value to the nation.

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[1] Section 102.c.4 of the National Aeronautics and Space Act of 1958 includes provision for the conduct of the aeronautical and space activities of the United States towards establishment of long-range studies of the potential benefits to be gained from, the opportunities for, and the problems involved in the utilization of aeronautical and space activities for peaceful and scientific purposes.

**4) The original NASA implementation of NIAC as an external organization managed above and across the mission directorates was effective**. When it was initially formed, NIAC was managed by a high-level agency executive concerned with the objectives and needs of all NASA enterprises and missions. The committee found that NIAC was most successful as a program with crosscutting applicability to NASA's enterprises and missions. When it was transferred to a mission-specific directorate, NIAC lost its alignment with sponsor objectives and priorities. To allow for sustained implementation of NIAC2 infusion objectives, the committee recommends that NIAC2 report to the Office of the Administrator, be outside mission directorates, and be chartered to address NASA-wide mission and technology needs. To increase NIAC2's relevance, NASA mission directorates should contribute thematic areas for consideration in the proposal solicitation process. The committee also recommends that this NIAC2 organization be funded and administered separately from NASA development programs, mission directorates, and institutional constraints. Future NIAC2 proposal opportunities should continue to be managed and peer-reviewed outside the agency.

**5) NIAC2 modifications should be made to improve effectiveness**. While NIAC's internet-based technical review and management processes were found to be effective and should be continued in NIAC2, the committee found a few policies that may have hastened NIAC's demise. Key among these was (1) the exclusive focus on revolutionary advanced concepts, (2) the exclusion of NASA personnel from participation in NIAC awards or research teams, and (3) the immaturity of NIAC Phase II products relative to that required for implementation as part of a future NASA mission or flight program.

By definition, visionary advanced concepts will not be near-term. However, in our committee discussions, it was felt that NIAC's complete focus on revolutionary concepts (as directed in its NASA SOW) was too long-term, creating a cultural mismatch between the NIAC products and its mission-focused sponsors and causing infusion difficulties for the NIAC innovators. As such, the committee recommends that the key selection requirement for NIAC2 proposal opportunities be that the concept is scientifically and/or technically innovative and has the potential to provide major benefit to a future NASA mission of 10 years and beyond. While 10 years and beyond includes concepts that could be 40 years or farther in the future, the committee felt that these modifications in focus would likely result in NIAC2 efforts with a higher probability of infusion into NASA's strategic planning process.

NIAC was formed to provide an independent, open forum for the external analysis and definition of space and aeronautics advanced concepts to complement the advanced concepts activities conducted within NASA; hence, NIAC solicitations were closed to NASA participants. However, NIAC was formed at a time when there was adequate funding internal to NASA for development of novel, long-term ideas. As internal NASA funding for advanced concepts and technology diminished or became more focused on flight-system development and operations, the cultural disconnect between the development activities internal and external to the agency grew, and transitioning of NIAC concepts to the NASA mission directorates became more difficult. The committee recommends that future NIAC2 proposal opportunities be open to principal investigators or teams both internal and external to NASA.

In addition, the committee believes that the potential for receipt of a NIAC2 Phase III award is needed to aid the transition of the most highly promising projects. Therefore, the committee recommends that future NIAC2 proposal opportunities include the potential selection of a small number of Phase III "proof of concept" awards for up to $5 million each over as much as 4 years to demonstrate and resolve fundamental feasibility issues and that such awards be selected jointly by NIAC2 and NASA management.

**6) NASA modifications should be made to improve effectiveness**. The lack of a NASA interface to receive the hand-off of promising projects was a persistent NIAC challenge. To improve the manner in which advanced concepts are infused into its future systems and to build a culture that continuously strives to advance technology, the committee recommends that NASA consider reestablishing an aeronautics and space systems technology development enterprise.[2] Such an organization would serve to preserve the leadership role of the United States in aeronautical and space systems technology.[3] Its NIAC2-oriented purpose would be to provide maturation opportunities and agency expertise for visionary, far-reaching concepts and technologies. NASA's considerations for such an enterprise should include implications for the agency's strategic plan, effective organizational approaches, resource distributions, field center foci, and mission selection process. Increased participation of NASA field center personnel, beyond review and management functions, should also significantly enhance advanced concept maturation and infusion into NASA mission planning. The committee also recommends identification of center technical champions and provision for the technical participation of NASA field center personnel in NIAC2 efforts. Participation of NASA personnel is expected to increase as NIAC2 projects mature.

**7) The budget requirement for a strong advanced concepts development activity reaches a steady-state value of approximately $10M per year**. Our committee believes that the NIAC was generally funded appropriately (approximately $4M/year) for its stated Phase I and Phase II objectives. We believe that NIAC2 proposal opportunities should be defined as follows: Phase I up to $100,000 each for 1 year; Phase II, up to $500,000 each for 2 years; Phase III proof-of-concept awards for up to $5 million each over as much as 4 years. Clearly, the number of such awards could be used as a control on the overall program budget. For example, in the first year of NIAC2, perhaps a dozen Phase I awards would be made for $1.2M, plus administrative costs. Including 4 Phase II awards in the following year would push the required yearly budget to approximately $2.2M (plus administrative costs). As a strawman, note that if NIAC2 funded 12 Phase I awards, 4 Phase II awards, and 1 Phase III award in each subsequent year, the budget requirement would increase by $1.25M each year until reaching a steady-state value of $8.2M in year six and beyond (plus administrative costs). In a strategy like this, the overall program budget is largely dependent on selection of the Phase III awards. If NASA saw value in the potential offered by multiple Phase III proposals, additional funds could be secured. If funding were tight in a given year, no Phase III awards would be made.

NIAC2 funding decisions should be made within the context of a well-funded NASA aeronautics and space systems technology enterprise that is both actively seeking advanced system concepts and maturing the requisite technological solutions. Large-scale technology development aspects of this enterprise were beyond the committee's charter, and would require considerably more funding than the $10M proposed for NIAC2. These larger funding issues are addressed in my response to the subcommittee's next question.

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[2] Similar findings are made in *A Constrained Space Exploration Technology Program: A Review of NASA's Exploration Technology Development Program,* The National Academies Press, Washington, D.C., 2008; and *America's Future in Space: Aligning the Civil Space Program with National Needs,* The National Academies Press, Washington, D.C., 2009.

[3] Section 102.c.5 of the National Aeronautics and Space Act of 1958 includes provision for the conduct of the aeronautical and space activities of the United States for the preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere.

In addressing the subcommittee's remaining questions, I am guided by my personal experience in NASA and academia. Although the NRC NIAC committee's discussions touched on these topics, this committee was not specifically tasked to address these broader subjects.

In response to the second question posed by the subcommittee, I would like to define the scope of a broadly focused long-term program dedicated to stimulate innovation and develop new concepts and capabilities, and then describe the results our nation should expect from such a program.

## Three Technology Development Classes and the Need for a Strengthened Capability-Based Technology Development Effort within NASA

In my experience, there are three general classes of technology development programs: mission-focused (near-term), discipline-based (long-term), and capability-based (mid-range). A NASA strongly positioned for the future should sponsor a blend of these three technology development classes, strategically guided by the results of a continuously engaged advanced concepts program. It is in this way that an advanced concepts program can be used to inform an organization's strategic planning process and provide value to its technology investment decisions. The success of such an enterprise will clearly be dependent on the group of program managers and systems engineers making technology readiness assessment and technology investment decisions for the agency. Passionate, hard-charging systems engineers and program managers who remain objectively focused on the long-term development needs of the agency, independent of the agency's institutional constraints, and out of the proverbial technology sandbox will be required. A series of competitively awarded activities spanning near-term, mid-term and long-term aeronautics and space systems needs is likely the best means of implementing a successful technology development program. Competitive awards should be made based on an objective assessment of the agency's strategic need, the proposed technical scope and product realism.

Mission-focused technology programs abound in most current large NASA programs. Consider, for example, NASA's human spaceflight program. In development of the Constellation architecture, priority was given to near-term systems with the goal of an early initial operational capability – existing technology with low risk was the Constellation mantra. In fact, funding from a wide range of NASA advanced technology programs was redirected to enable this capability. However, even with its near-term focus and budgetary challenges, the Constellation program required and funded a small number of mission-focused technologies to enable qualification of the key technologies required for mission success. These mission-focused technology programs include a lunar-return capable heatshield, an autonomous landing and hazard avoidance system for lunar landing operations, and lunar in-situ resource utilization.[4] Without such technological advances, NASA's current approach to returning humans to the Moon would be dramatically impacted. Similar mission-focused technology investments have allowed NASA's robotic exploration program to pursue advanced science missions like the Mars Science Laboratory and Webb Space Telescope. Clearly, these are important investments that require NASA funding. However, these mission-focused activities are not the only technology investments that an agency that prides itself on innovation and pushing-the-boundary should pursue.

Within NASA, the ARMD Fundamental Aeronautics program is the only present program of which I am aware that is pursuing discipline-based technological solutions. Longer term by nature and generally funded at a much lower level, these technology advances are often

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[4] *A Constrained Space Exploration Technology Program: A Review of NASA's Exploration Technology Development Program*, The National Academies Press, Washington, D.C., 2008.

pursued with the promise of enabling dramatic performance improvements in one or more aerospace disciplines, and the potential for major system advances across multiple future programs. While ARMD funding is largely directed internal to NASA and its aeronautics challenges, examples of possible discipline-based technology investments include laminar flow control technology, high-temperature materials and structures, hypersonic airbreathing propulsion, advanced in-space propulsion, robust navigation and control algorithms, high-efficiency solar power systems, radiation protection systems, and inflatable structures. In addition, NASA can now offer unique, discipline-based microgravity research opportunities through effective utilization of the International Space Station.

The United States boasts a tremendously successful robotic Mars program. Continuous orbital observations of the Mars surface have been made for more than a decade and six robotic systems have now been placed on the surface of Mars. While each of these six landed missions has been an incredible technological accomplishment in itself, these robotic systems have each landed less than 0.6 metric tons within landing footprints on the order of hundreds of kilometers. At present, robotic exploration systems engineers are struggling with the challenges of increasing landed mass capability to just 1 metric ton (less than half the Earth weight of a 2009 Ford Explorer) while improving landed accuracy to 10 kilometers for the Mars Science Laboratory project. Meanwhile, the planning of subsequent robotic exploration missions under consideration for the 2020 decade may require several metric tons in landed mass capability and current plans for human exploration of Mars call for landing 40-80 metric ton surface elements within close proximity (tens of meters) of pre-positioned robotic assets. These future mission requirements cannot be met with NASA's present suite of entry, descent and landing technologies and are one reason that human Mars exploration is viewed as a "bridge too far" by many in the aerospace and public policy communities. However, analysis suggests that there are a handful of promising entry, descent and landing capabilities that may prove feasible for these larger landed systems, enabling future Mars exploration concepts of which today we can only dream. These technologies are termed capabilities because these same general systems may also prove advantageous for Earth-return missions or missions to other planets – such developments are not specific to a single mission. Additional capability-focused technology needs abound in deep space exploration, astrophysics, aeronautics, and Earth science. In each case, NASA technology investment is critical – for without such an investment, these future missions will simply not occur.

Strategic assessment of our nation's future spaceflight technology needs was performed by both the Aldridge Commission[5] in 2004 and the Augustine Commission[6] in 2009. Each commission concluded that successful development of a set of enabling technologies (or capabilities) is critical to attainment of human and robotic exploration objectives within reasonable schedule and affordable cost. The NASA Authorization Act of 2008 furthered this sentiment by codifying it into law. Section 405 of this Act states, "*A robust program of long-term exploration-related research and development will be essential for the success and sustainability of any enduring initiative of human and robotic exploration of the solar system.*" This Act further states that this program shall not be tied to specific flight projects. I strongly agree with the capability-based technology sentiment expressed by these two Presidential Commissions and the NASA Authorization Act of 2008.

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[5] *Report on the President's Commission on Implementation of U.S. Space Exploration Policy: A Journey to Inspire, Innovate and Discover*, June 2004.

[6] *Summary Report on the Review of U.S. Human Spaceflight Plans*, September 2009.

While mid-term, capability-based technology investments are perhaps the most critical for a forward-looking Agency like NASA; within NASA today, this type of technology investment is minimal. NASA presently invests approximately $1.35B on a range of near-term, mid-range and long-term technologies.[7] Approximately two-thirds of this investment is directed towards near-term mission-focused technologies that are strongly coupled to NASA's existing programs. This allocation leaves approximately $0.45B (less than 3% of NASA's total budget) for capability-based technology development and discipline-based fundamental research that is not tied to existing program requirements. However, at present, a majority of these remaining funds are allocated to the longer-term ARMD Fundamental Aeronautics program, leaving little mid-range capability-based technology investment.

### Anticipated Results from a Broadly Focused Long-Term NASA Program to Develop Advanced Concepts and their Associated Technologies

Many positive outcomes are likely from a long-term, broadly focused NASA advanced concepts and technology development program that include mission-focused, capability-based and discipline-based components. Chief among these consequences is the provision of a more vital and productive aeronautics and space future than our country has today. Each year, in the first lecture of my freshman *Introduction to Aerospace Engineering* class, I share with these recent high-school graduates a list of accomplishments that I believe our nation's civil aeronautics and space program is capable of achieving in my lifetime:

**Ten Anticipated Paradigm-Changing Civil Aeronautics and Space Advances**

1) Quantify Causes, Trends and Effects of Long-Term Earth Climate Change
2) Accurately Forecast the Emergence of Major Storms and Natural Disasters
3) Develop and Utilize Efficient Space-Based Energy Sources
4) Prepare an Asteroid Defense
5) Identify Life Elsewhere in our Solar System
6) Identify Earth-like Worlds Around Other Stars
7) Initiate Interstellar Robotic Exploration
8) Achieve Reliable Commercial Low-Earth Orbit Transportation
9) Achieve Affordable Supersonic Business Travel
10) Achieve Permanent Human Presence Beyond the Cradle of Earth

Advances of this type are more than a single professor's dream – they are a spark to a technology-based economy, an international symbol of our country's scientific and technological leadership, and a component of the remedy to our nation's scientific and mathematics literacy challenges. I genuinely believe that game-changers like these are within our nation's grasp. Capability-based technology investment, focused leadership and stability of purpose are the only elements holding us back. Landing humans on Mars requires an investment in advanced technology, as does developing a telescope capable of detecting Earth-size planets around other stars, flying a new generation of human-rated launch systems, or identifying life elsewhere in our solar system. Our nation needs to dream big, and large goals, like these, are precisely the kind of objectives that our nation has come to expect of NASA. It is equally clear that in the absence of sustained, broad-based technology investments, the United States will not continue to make significant advances in aeronautics, space, and the associated sectors of our society. Investments of this scale will not be without cost. I believe that our nation would be well served by investing at least 10% of NASA's budget in support of the technologies required to dramatically advance entirely new aeronautics and space endeavors (in contrast to an investment of less than 3% today).

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[7] *NASA Innovation and Technology Initiative: Enabling NASA's Future and Addressing National Needs*, Briefing to NRC ASEB by Dr. Laurie Leshin, NASA, October 2009.

In this same class, I often ask the students why they are choosing to become aerospace engineers. In general, these 18-year olds are motivated by a strong desire to contribute to humanity's future by solving our nation's grand technological challenges. They want to work with others (and in organizations) who feel the same way. As such, a well managed, broad-based advanced concepts and technology development enterprise can serve as a catalyst to revitalize our nation's aerospace workforce with the best and brightest of tomorrow. Such an organization can also serve to demonstrate that NASA continues to be a driver of scientific innovation, engineering creativity and technological competitiveness for our country and around the world.

NASA technology innovation efforts are also bound to stimulate the university and commercial sectors, create new business and increase the number of high-tech jobs across our nation. As a small-scale example, NIAC efforts contributed to the launch of a new business division within ENSCO and two entirely new businesses (Space Elevator: Black Line Ascension and Liftport).

In response to the third question posed by the subcommittee, I would like to briefly discuss the additional uncertainty and risk associated with developing new concepts and technologies within NASA's flight projects.

Technology Development within NASA's Missions Contribute Significant Cost and Schedule Risk
Implementation of NASA space flight missions is fraught with complex systems engineering challenges due to the extreme environment in which these systems must reliably operate. Completing a spaceflight mission within its established budget and schedule constraints is one of the most difficult undertakings in the engineering field. As such, I have great respect for those within NASA who have succeeded in these endeavors. These missions demand a focus on technical excellence across the organization, a systems engineering approach to project implementation, technical insight and crisp decision-making from project managers, clear communication across the organization, and early risk identification, prioritization, and mitigation. In addition, trades between performance, cost, schedule and risk are generally constrained by program-level decisions and public policy decisions made outside the project's control. In my view, adding requirements for technology development to a NASA flight project in the implementation phase is inherently risky and a poor program management practice.

In March 2009, in testimony presented before this subcommittee entitled, *NASA Projects Need More Disciplined Oversight and Management to Address Key Challenges*, a GAO representative described her analysis of thirteen NASA flight projects in the implementation phase. In this project phase, systems design is completed, scientific instruments are integrated, and the flight system is fabricated and prepared for launch. Prior to entering the implementation phase, it is standard NASA practice to have finalized requirements, concepts and technologies and establish a baseline project plan. Ten of the thirteen NASA projects in the implementation phase assessed by the GAO experienced significant cost and/or schedule growth from their project baselines. Of the five causes of cost and/or schedule growth cited by the GAO, two issues pertain directly to technology development risk: technology immaturity and modifications required to previously considered heritage items. The common symptom of these two causes is a technological readiness considerably below that estimated by the project. The GAO report concludes, "Simply put, projects that start with mature technologies experience less cost growth than those that start with immature technologies." I fully agree with this statement.

NASA also knows this lesson. In fact, NASA requires all technologies used in its competitive missions to be at a technology readiness level of six (system/subsystem model or prototype demonstration in a relevant environment) or higher by the beginning of the project implementation phase. In a competitive proposal, failure to have such a technology maturation plan is cited as a major weakness. As such, few, if any, competed missions begin implementation while still developing technology. However, this same approach is not generally applied to NASA's larger space flight programs, which often rely on large technology advancements as part of project implementation due to the significant performance gains that they are attempting to achieve. As a result, large, non-competed projects tend to encounter significant cost overruns and/or schedule delays as a result of technology risk. Insisting on an adequate formulation phase in which technology risk is firmly retired, before committing project implementation funding, is the most straightforward means for reducing the cost and schedule risk of these large NASA missions.

In response to the fourth question posed by the subcommittee, I would like to briefly discuss the time horizons required for the development of advanced concept and technology development programs.

## Time Horizons on Advanced Concept and Technology Development Programs

A long-term, broadly focused NASA advanced concepts and technology development enterprise should span multiple timeframes in which the maturation plan for a given technology should be coupled to the agency's strategic planning process through ongoing NIAC2 advanced concept studies. Within this enterprise, one can envision a blend of technology development timeframes spanning 2-5 years for mission-focused technology (moderate $ investment), 5-15 years for capability-based technology (large $ investment), and 15-40 years for discipline-based technology (modest $ investment). Competitive awards across these technology classes should be made on a 2-3 year cycle depending on the milestones achieved and funding availability. Technology project development lifecycles spanning 2-5 years are anticipated. In this scenario, the technology development enterprise should partner with NASA's existing flight programs such that the mission-focused technologies it funds benefit from at least a 50% cost contribution from the relevant mission directorate. This strategy should allow for capability-based technologies, which are not tied to NASA's existing missions, to dominate the investment portfolio of the technology development enterprise. This emphasis on capability-based technology is absent in NASA today. A broad range of discipline-based investments should also be funded at a lower level.

Use of NIAC2 as a long-term asset to inform NASA's strategic planning process is a key component of this plan. NIAC2 can look out for advanced concepts beyond the current development programs. It can work on the edges where requirements are not yet known, focused on what program managers would want if they knew that they needed it. However, it is also clear that for this independent organization that nurtures technology push to succeed, it must be partnered with a substantive NASA enterprise of technology pull, managed at the agency-level and working in concert with NASA's existing mission directorates.

## Summary

There is little capability-based technology development within NASA today and no NASA organization responsible for solicitation, evaluation, and maturation of advanced concepts or responsible for subsequent infusion of worthy concepts into NASA's strategic planning process. In my view, this is not acceptable for an agency whose purpose includes demonstrating this nation's scientific and technological prowess, or one that is trying to inspire the next generation of engineers and scientists. A technology-poor NASA greatly hampers our aeronautics and space flight development programs. We cannot continue to rely on 1970's-era technology to land systems on Mars, particularly if we want to build towards eventual human exploration. We cannot continue to explore the solar system robotically without advanced in-space propulsion and atmospheric flight technologies as part of our future mission portfolio. We cannot plan a sustainable human exploration program without strong technology leverage. Strategic assessment of our nation's future spaceflight technology needs was performed by both the Aldridge Commission in 2004 and the Augustine Commission in 2009. Each commission concluded that successful development of a set of enabling technologies (or capabilities) was critical to attainment of space exploration objectives within a reasonable schedule and affordable cost. The NASA Authorization Act of 2008 furthered this sentiment by codifying it into law. Based on these inputs, I suggest NASA establish a formal enterprise to continuously evaluate, prioritize, and mature these technologies in the relevant environments. Within this enterprise, a blend of technology development activities spanning mission-focused technology (2-5 year maturation timeframe, moderate $ investment), capability-based technology (5-15 year maturation timeframe, large $ investment), and discipline-based technology (15-40 year maturation timeframe, modest $ investment) should be pursued.

Our nation would be well served by investing at least 10% of NASA's budget in support of the technologies required to dramatically advance entirely new aeronautics and space endeavors (in contrast to an investment of less than 3% today). This investment would include a small amount for advanced concepts so difficult to achieve that their chance of individual success within a decade is less than 10%, yet concepts so innovative that their success could serve as game-changers for this vital, national industry. Our nation needs to dream big, and large goals are precisely what our nation has come to expect of NASA. Major breakthroughs are needed to address our society's energy, health, transportation, and environment challenges. While NASA investments alone will not solve these grand challenges, NASA has proven to have a unique ability to attract and motivate many of the country's best young minds into educational programs and careers in engineering and science. Although it is not possible to predict which advanced aerospace concepts will produce paradigm-shifting results, it is certainly true that, in the absence of research on such concepts, the United States will not make revolutionary technological advances in aeronautics and space and long-term societal goals in these and related areas will remain beyond our reach.