NASA'S AERONAUTICS MISSION: ENABLING THE TRANSFORMATION OF AVIATION

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE AND AERONAUTICS

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

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C O N T E N T S

June 26, 2019

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Appendix II: Additional Material for the Record

NASA'S AERONAUTICS MISSION: ENABLING THE TRANSFORMATION OF AVIATION

WEDNESDAY, JUNE 26, 2019

House of Representatives,
Subcommittee on Space and Aeronautics,
Committee on Science, Space, and Technology,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 3:16 p.m., in room 2318 of the Rayburn House Office Building, Hon. Kendra Horn [Chairwoman of the Subcommittee] presiding.

SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

HEARING CHARTER

"NASA's Aeronautics Mission: Enabling the Transformation of Aviation"

June 26, 2019
2:00 p.m.
2318 Rayburn House Office Building

PURPOSE

The purpose of the hearing is to review the programs, activities and plans of the National Aeronautics and Space Administration's Aeronautics Research Mission Directorate, and associated issues.

WITNESSES

- **Dr. Jaiwon Shin,** Associate Administrator, Aeronautics Research Mission Directorate, National Aeronautics and Space Administration
- **Dr. Alan H. Epstein,** R.C. Maclaurin Professor Emeritus of Aeronautics and Astronautics, Massachusetts Institute of Technology; Chair, Aeronautics and Space Engineering Board, National Academies of Sciences, Engineering, and Medicine
- **Dr. Ilan Kroo,** Professor of Aeronautics and Astronautics, Stanford University
- **Dr. Mark Lewis,** Director, IDA Science & Technology Policy Institute; Professor Emeritus of Aerospace Engineering, University of Maryland

OVERARCHING QUESTIONS

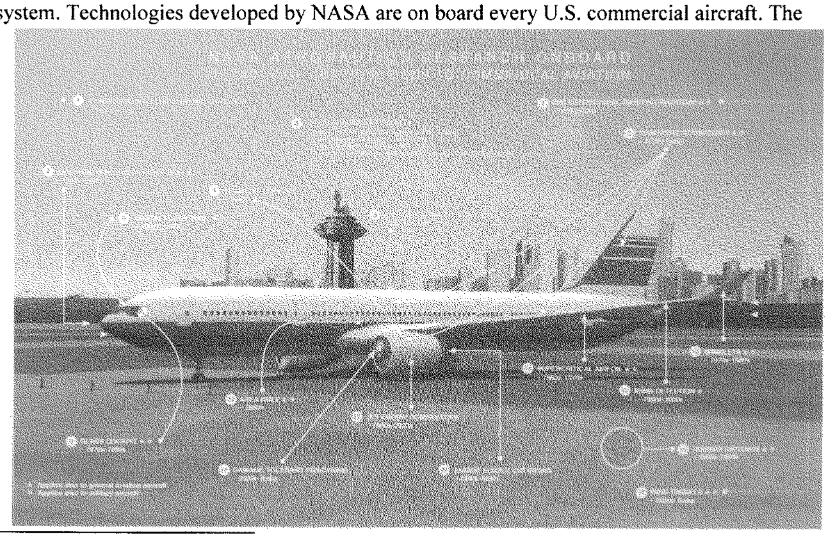
- *What are the emerging challenges and opportunities in aeronautics and aviation, and to what extent is NASA positioned to address them?*
- *How does the NASA Aeronautics Research Mission Directorate prioritize its research activities and programs?*
- *What is NASA's role in increasing the efficiency, safety, and sustainability of the United States' aviation system?*
- *What facilities, workforce skills, and capabilities are needed to enable the transformation of aviation, and how can NASA help meet those needs?*

BACKGROUND

Aviation is critically important to the U.S. economy, accounting for more than $1.6 trillion of U.S. economic activity in 2014.[1] A global leader, the U.S. aerospace industry operates at a positive trade balance ($87.7 billion in 2018).[2] The NASA Aeronautics Research Mission Directorate (ARMD) plays a key role in conducting research and solving problems for the future of aviation. NASA's legacy began in aeronautics—the science of traveling through the air—with its predecessor, the National Advisory Committee for Aeronautics (NACA), which was established by Congress in 1915 as an independent agency that reported to the President. The National Aeronautics and Space Act of 1958 that established NASA incorporated the activities of NACA and included among the eight objectives of the nation's aeronautical and space activities both "*the improvement of usefulness, performance, speed, safety, and efficiency of aeronautical and space vehicles*" and "*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.*"[3] NASA has a history of meeting these objectives by performing basic research and development (R&D) and providing research findings to the aviation industry and broader community.

Aeronautics Research Mission Directorate Activities

NASA's aeronautics research directly affects the success and future of the U.S. air transportation system. Technologies developed by NASA are on board every U.S. commercial aircraft. The



[1] "The Economic Impact of Civil Aviation on the U.S. Economy," FAA, November 2016. Available at: https://www.faa.gov/about/plans_reports/media/2017-economic-impact-report.pdf
[2] "Leading Indicators for the U.S. Aerospace Industry," International Trade Administration, March 15, 2019. Available at: https://www.trade.gov/td/otm/assets/aero/LeadingIndicators.pdf
[3] Title 51, U.S. Code, Section 20102(d)

figure above highlights NASA's contribution to commercial aviation.[4] In addition, NASA has a history of working with the Federal Aviation Administration (FAA), the United Nations' International Civil Aviation Organization (ICAO), and standards bodies to conduct underlying research and tests and deliver the data and tools to help inform the development of aviation regulations and standards.[5]

NASA's ARMD is guided by a strategic implementation plan,[6] which lays out the approach for addressing growing demand for global air mobility, increasing demands for energy efficiency and sustainability, and enabling convergence between traditional aeronautics disciplines and other emerging technologies. The plan identifies six research thrusts:

(1) Safe, Efficient Growth in Global Operations,
(2) Innovation in Commercial Supersonic Aircraft,
(3) Ultra-Efficient Commercial Vehicles,
(4) Transition to Alternative Propulsion and Energy,
(5) Real-Time System-Wide Safety Assurance, and
(6) Assured Autonomy for Aviation Transformation.

According to the strategic implementation plan, the ARMD formulated these "Strategic Thrusts" to "*act as the link between its strategic vision and its research plans*" and that, taken together, they "*constitute a vision for aviation and the ARMD's plan to enable the transformation of aviation to meet future needs.*" To address these strategic thrusts, ARMD manages four major programs, each focused on a specific research area:

- Airspace Operations Safety Program (AOSP), which safely increases the throughput and efficiency of the National Airspace System (NAS).
- Advanced Air Vehicles Program (AAVP), which enables advances for a wide range of civil aircraft that are safer, more energy efficient, and have smaller environmental impact.
- Integrated Aviation Systems Program (IASP), which conducts research on promising concepts and technologies at an integrated system level.
- Transformative Aeronautics Concepts Program (TACP), which demonstrates initial feasibility in multi-disciplinary concepts, including where non-aeronautics technologies converge with aeronautics, to create new opportunities in aviation.

Aeronautics Research Mission Directorate Fiscal Year 2020 Request

The NASA Fiscal Year (FY) 2020 budget request for ARMD, as detailed in the table below, proposed a total of $666.9 million, a $58.1 million (8 percent) reduction from the FY 2019 enacted appropriation. The proposed reduction is largely due to the transfer of $56 million for the

[4] NASA Image, "NASA Aeronautics Research Onboard: Decades of Contributions to Commercial Aviation." Available at: https://www.nasa.gov/sites/default/files/files/c_litho_12_07_09_v2.pdf
[5] "NASA's Research Efforts and Management of Unmanned Aircraft Systems" NASA OIG, IG-17-025. September 2017. https://oig.nasa.gov/docs/IG-17-025.pdf
[6] "NASA Aeronautics: Strategic Implementation Plan, 2017 Update." Available at: https://www.nasa.gov/aeroresearch/strategy

management of the Aeronautics Evaluation and Testing Capabilities (AETC) Project[7] out of ARMD and into the Safety, Security, and Mission Services account.

Budget Authority (in $ millions)	Actual FY 2018	Enacted FY 2019	**Request FY 2020**	FY 2021	FY 2022	FY 2023	FY 2024
Airspace Operations and Safety Program	118.7	--	**121.2**	130.6	133.5	136.2	138.9
Advanced Air Vehicles Program	237.7	--	**188.1**	203.3	212.2	219.3	224.2
Integrated Aviation Systems Program	221.5	--	**233.2**	209.4	202.2	97.1	87.2
Transformative Aero Concepts Program	112.2	--	**124.4**	130.3	132.3	134.6	136.7
Total Budget	**690.0**	725.0	**666.9**	**673.6**	**680.3**	**587.1**	**587.0**
Change from FY 2019			**-58.1**				
Percentage change from FY 2019			**-8.0%**				

Energy Efficiency and Environmental Sustainability

According to the International Air Transportation Association (IATA), the number of passenger airplane trips could nearly double by 2037,[8] raising concerns about broader environmental and community impacts, including attendant increases in carbon dioxide (CO_2) emissions and noise. Aviation currently accounts for about 2 percent of global annual CO_2 emissions, and 90 percent of those emissions are from aircraft carrying 100 or more passengers.[9] A 2016 National Academies report, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*,[10] recommended that agencies and organizations in government, industry, and academia prioritize efforts to reduce aviation CO_2 emissions over the next 10-30 years, including advances in aircraft-propulsion integration, such as changes in aircraft configurations; improvements in the efficiency of gas turbine engines (jet engines); development of turboelectric propulsion systems; and advances in sustainable alternative jet fuels, which can be used with existing jet propulsion systems to reduce carbon emissions.

NASA contributes to increasing energy efficiency and environmental sustainability through several ARMD programs and projects. In collaboration with industry partners, NASA developed hybrid gas-electric propulsion concepts and demonstrated a 500 kilowatt hybrid electric powertrain system. NASA also started work on an X-57 Maxwell experimental aircraft, which will inform the ability to design, build, and operate an all-electric system. In addition, NASA has collaborated with partners to test blends of alternative fuels in aircraft operations. NASA's work on noise reduction includes testing technologies to reduce landing gear noise and demonstrating a technology to reduce the drag within a jet engine that lowered noise during take-off-and-landing. Among activities planned for FY 2020 are continued work on advanced wing concepts

[7] The AETC Project, currently managed under the ARMD account, consists of NASA's aerosciences test facilities, primarily wind tunnels. ARMD is the primary user of the AETC facilities, but the Human Exploration and Operations, Science, and Space Technology mission directorates are also users.
[8] "IATA Forecast Predicts 8.2 billion Air Travelers in 2037." IATA, October 2018. https://www.iata.org/pressroom/pr/Pages/2018-10-24-02.aspx
[9] "Fact Sheet: Climate Change and CORSIA." IATA, May 2018. https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-climate-change.pdf
[10] National Academies of Sciences, Engineering, and Medicine. 2016. *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. Washington, DC: The National Academies Press. https://doi.org/10.17226/23490.

that have the potential to lead to quieter, lighter, and more efficient aircraft and plans to carry out the first test flight of the X-57 Maxwell aircraft to test electrical systems. NASA also plans, in FY 2020, to begin an effort to achieve, over multiple years, a 1 megawatt power electric propulsion system, which has been found to potentially benefit a range of aircraft sizes.

Supersonic Flight

Typical commercial airplanes cruise at speeds of 450-550 miles per hour, well below the speed of sound, which is approximately 770 miles per hour. A supersonic aircraft travels faster than the speed of sound and produces a continuous stream of shock waves. A listener on the ground below a supersonic plane hears a loud, thunder-like clap of sound called a "sonic boom" from the sudden changes in air pressure from the shock wave. In addition to causing the loud noise, sufficiently intense sonic booms can even break glass or otherwise damage structures. Civil and commercial supersonic flight over land has thus been banned in the U.S. since 1973.[11]

The Concorde, developed by companies in Great Britain and France, was the only commercial supersonic airliner and flew transatlantic routes from 1978 until its retirement in 2003. Through many years of basic R&D in supersonics, NASA has developed designs for aircraft that increase efficiency and significantly reduce the strength of the sonic boom. NASA has also developed sophisticated tools and techniques for testing, collecting and analyzing data, and modeling supersonic flight.[12] To that end, NASA initiated in 2018 the Low Boom Flight Demonstration (LBFD) mission, which starts with the development of the X-59 Quiet Supersonic Technology (QueSST) aircraft, designed with a unique shape that minimizes the sonic boom. NASA will then perform test flights of the X-59 over diverse populations and geographical locations within the U.S. "*to develop a low-boom community response database that will be provided to U.S. and international regulators in support of their development of a noise-based standard for supersonic overland flight.*"[13] NASA expects to deliver finalized LBFD data in FY 2025 to FAA and ICAO to inform the development of regulations allowing for supersonic overland flights.

Safe Integration of UAS into the Airspace

Commonly referred to as a "drone," an unmanned aircraft system (UAS) is any aircraft that operates without a pilot or crew on board, either remotely or entirely autonomously. While UAS already play a significant role in military applications, they also could have wide applications in civil aviation. NASA is particularly focused on developing the technologies and providing the data to enable the safe integration of UAS into the airspace. In FY 2020, NASA plans to complete the UAS Integration into the National Airspace (NAS) and UAS Traffic Management (UTM) projects, the results of which will be delivered to the FAA.

[11] Title 14, U.S. Code of Federal Regulations, Section 91.817
[12] "70 Years of Supersonic Flight: NASA Continues to Break Barriers." Available at: https://www.nasa.gov/centers/armstrong/feature/70_years_supersonic_flight.html
[13] NASA FY 2020 Budget Request, Congressional Justification. Available at: https://www.nasa.gov/sites/default/files/atoms/files/fy_2020_congressional_justification.pdf

Urban Air Mobility

Urban Air Mobility (UAM) refers to a new air transportation concept for short-distance flight (few to tens of miles) within a major metropolitan area by aircraft carrying either passengers or cargo and controlled either manually or autonomously. Examples of potential UAM systems range from "last-mile" small package delivery to multi-passenger "air taxis" that offer on-demand private transport for 2-5 people at a time as app-based services do now by car. UAM systems are generally envisioned to be electric vertical takeoff and landing aircraft (eVTOLs), requiring no runways, instead landing in open spaces or on city rooftops. The current era of public and private UAM development was catalyzed by a NASA aerospace engineer's 2010 paper on electric propulsion as a "*game changing technology*" for eVTOLs.[14]

UAM has the potential to fundamentally alter urban transportation by lifting some of the traffic congestion on the street to the air.[15] For some use cases, UAM passenger transportation could reduce greenhouse gas emissions: a recent study concluded that "*[electric] VTOLs offer fast, predictable transportation and could have a niche role in sustainable mobility.*"[16]

Companies around the world, including ones based in the U.S., Europe, Brazil, and China, are making significant investments in UAM R&D and have begun test flights. Governments beyond the U.S. are also looking toward a UAM future: for example, in 2018, Japan's government funded a public-private partnership to enable a viable UAM market by 2023.[17]

NASA recently commissioned two UAM market analyses, both of which were released in November 2018. One study carried out by Booz Allen Hamilton[18] found that markets for air taxis and airport shuttles could be viable, with a best-case scenario combined market value of $500 billion. The second study, by Crown Consulting, Inc.,[19] found that last-mile package delivery could be profitable by 2030, with 500 million annual deliveries. That study also found that "air metro," with pre-determined routes and schedules, and set stops in high traffic areas, could be profitable by 2028 with 130 million passenger trips, and grow to 740 million passenger trips in 2030. Both studies caution that their results significantly depend on overcoming challenges in a number of areas, including safety, technology, regulations, and public acceptance.

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[14] Moore, Mark. "NASA Puffin Electric Tailsitter VTOL Concept." 10th American Institute of Aeronautics and Astronautics Aviation Technology, Integration, and Operations Conference Proceedings, September 2010. https://doi.org/10.2514/6.2010-9345

[15] Arieno, Vanessa. "Are Flying Cars Just Science Fiction? Urban Air Mobility Could Solve Some of Transportation's Most Pressing Problems." *Newsweek*. February 1, 2019. https://www.newsweek.com/flying-cars-science-fiction-urban-air-mobility-solve-transportation-problems-1309638

[16] Kasliwal, Akshat; Furbush, Noah J.; Gawron, James H.; et al. "Role of Flying Cars in Sustainable Mobility." *Nature Communications*, 10: 1555. April 9, 2019. https://www.nature.com/articles/s41467-019-09426-0

[17] Boyd, John. "Japan's Roadmap for Flying Cars." *IEEE Spectrum*. February 11, 2019. https://spectrum.ieee.org/cars-that-think/transportation/alternative-transportation/japan-wont-be-grounded-when-it-comes-to-flying-cars

[18] "Executive Briefing: Urban Air Mobility (UAM) Market Study." Booz Allen Hamilton for NASA. Available at: https://www.nasa.gov/sites/default/files/atoms/files/bah_uam_executive_briefing_181005_tagged.pdf

[19] "Urban Air Mobility (UAM) Market Study." Crown Consulting, Inc. for NASA. Available at: https://www.nasa.gov/sites/default/files/atoms/files/uam-market-study-executive-summary-v2.pdf

NASA ARMD's primary role in UAM is targeted at advancing the safe integration of UAM vehicles into the national airspace system, including addressing challenges across operations and community acceptance. In 2020, NASA plans to initiate a Grand Challenge, an annual series of UAM ecosystem-wide safety and integration scenarios that would both promote public confidence in UAM safety and facilitate community-wide learning.[20] NASA issued a request for information (RFI) from stakeholders to inform the Grand Challenge in fall 2018.[21]

NASA ARMD reactivated the National Academies of Sciences, Engineering, and Medicine's Aeronautics Research and Technology Roundtable[22] in 2018 to focus on UAM. NASA has also contracted the National Academies to conduct a consensus study to assess the feasibility of a safe and efficient UAM system. The study is anticipated to be released in 2020.[23]

Hypersonics

While "supersonic" flight is at any speed above the speed of sound, flight faster than five times the speed of sound is generally referred to as "hypersonic." Advancement of hypersonic missiles that can travel at ten to twenty times the speed of sound, or "hypersonics," is a near-term priority of the U.S. military to improve the capabilities of air defense and attack, especially as foreign allies and adversaries make advances in the technology.[24] NASA's role is in fundamental hypersonics research for potential civil applications—like reaching low Earth orbit (LEO) or commercial air travel—and the agency carries out that research in partnership with the FAA and Department of Defense (DoD).

NASA ARMD funds hypersonics research in the Advanced Air Vehicle Program budget line. As an example, NASA works on hypersonics propulsion R&D because "*one of the key challenges for hypersonics is creating a propulsion system that can operate at slower speeds for takeoff and landing and transition to high-speed operation in flight.*"[25] NASA's hypersonics research activities include propulsion methods and the accompanying algorithms and techniques to improve that transition for both national security and aviation industry purposes.

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[20] NASA UAM Grand Challenge project page: https://www.nasa.gov/uamgc
[21] ARMD UAM RFI available at:
https://www.fbo.gov/spg/NASA/DFRC/OPDC20220/18AFRC19S0001/listing.html
[22] Aeronautics Research and Technology Roundtable of the National Academies of Sciences, Engineering, and Medicine. Project information page: https://www8.nationalacademies.org/pa/projectview.aspx?key=50607
[23] "Urban Air Mobility Research and Technology" Study Committee of the National Academies of Sciences, Engineering, and Medicine. Project information page:
https://www8.nationalacademies.org/pa/projectview.aspx?key=51434
[24] Smith, R. Jeffrey. "Hypersonic Missiles are Unstoppable. And They're Starting a New Global Arms Race." *The New York Times Magazine*. June 19, 2019. https://www.nytimes.com/2019/06/19/magazine/hypersonic-missiles.html
[25] NASA FY 2020 Budget Request, Congressional Justification. Available at:
https://www.nasa.gov/sites/default/files/atoms/files/fy_2020_congressional_justification.pdf

Chairwoman HORN. This hearing will come to order. Without objection, the Chair is authorized to declare recess at any time. Good afternoon, and welcome. I'm especially pleased to welcome our distinguished group of witnesses today, and want to thank you all for being here, and for your patience as we were on the floor with votes.

We are on the cusp of transformational changes in aviation. Not only is the commercial aviation market robust with global passenger air transport, but is projected to double by 2040. Emerging new markets and innovative technologies are also literally changing what we see on the horizon. These innovations are not just about the novelty of pizza and package deliveries to your door by flying drones, or the flying cars that we've always envisioned from the Jetsons era. They're about economic impact, competitiveness, and American jobs.

One estimate projects that the integration of unmanned aircraft systems into the airspace could lead to 100,000 jobs and $82 billion in economic activity. Market projections for urban air mobility are also in the billions of dollars. Our U.S. economy stands to gain significantly from these emerging aviation markets. Yet, when combined with the current impact of civil aviation, which in 2014 provided over 10 million jobs, and represented $1.6 trillion of total U.S. economic activity, and accounted for 5.1 percent of U.S. GDP, the importance of commercial aviation to our Nation's economic growth is magnified. In my own State of Oklahoma, aviation and aerospace represent the second largest employment sector across the State, a fact that many people don't know. According to a study by the Oklahoma Aeronautics Commission, aviation, aerospace, and associated activities provide for over 200,000 jobs, and about $44 billion in economic impact.

While there is much to celebrate in the success of U.S. commercial air transportation, our competitiveness on the global market is increasingly harder to maintain. The International Aviation and Transportation Association predicts that by the mid-2020s China will displace the United States as the world's largest aviation market. That's why Federal research investments to transform this industry are important, and why we are here today to examine NASA's (National Aeronautics and Space Administration's) Aeronautics mission and enabling role. Because maintaining our success, and realizing the opportunities before us, means overcoming challenges. Airplane noise complaints to the FAA (Federal Aviation Administration) have seen sharp increases; growth in air transportation is stretching the capacity of our national airspace system, and new entrants, including drones and urban air vehicles, add complexity to the airspace that must be safely managed if we are to be successful.

Perhaps the most pressing of all is the impact of air transportation on the environment. Not only does commercial aviation account for about 2 percent of human-induced global carbon emissions, the jet fuel that produces those emissions represents a significant portion of commercial airline costs. With expected compound annual growth rates of about 3.5 percent in air passengers, the problem will only get worse. Sustainability is not only critical to the environment, it's becoming a competitive advantage.

At this year's Paris Air Show, which ended just days ago, Chief Technical Officers (CTOs) of seven of the world's leading aviation manufacturers came together in an unprecedented union to commit to a sustainable future for commercial air transportation. I am submitting a copy of their statement for the record. And that's where NASA's aeronautic research plays a vital role, carrying out fundamental research to improve efficiencies, enabling the safe integration of new entrants into the airspace, testing new aircraft systems and designs, and developing enabling technologies and techniques to mitigate the environmental impacts of aviation.

The question before us today is, are we, in Congress, and the Federal Government, doing enough? Are we making the necessary investments to help realize the full potential of emerging markets that have significant implications for U.S. competitiveness and economic growth? Do we have the workforce facilities to support NASA's aeronautics R&D (research and development), and the growing industries, and will our R&D efforts help keep us on track to meet goals for commercial aviation, to achieve carbon neutral growth in 2020, and reduce CO_2 emissions by 50 percent of what they were in 2005 by 2050?

In closing, I'd like to say this: The proposal for aeronautical research and technology in NASA's Fiscal Year 1994 budget request was 2-1/2 times the 2019 year dollars than the Administration's proposed investment in FY 2020 NASA Aeronautics' research programs. Recognizing the magnitude of the economic impact of U.S. commercial aviation today, and the challenges and opportunities ahead, the question is, is that sufficient? Thank you.

[The prepared statement of Chairwoman Horn follows:]

Good afternoon, and welcome. I'm especially pleased to welcome our distinguished group of witnesses. Thank you for being here.

We're on the cusp of transformational changes in aviation. Not only is the commercial aviation market robust with global passenger air transport projected to double by about 2040, emerging new markets and innovative technologies are literally changing what we see on the horizon. These innovations are not just about the novelty of pizza and package deliveries to your door by drones or the "flying cars" of the Jetsons cartoon, they're about economic impact, competitiveness, and American jobs. One estimate projects that the integration of unmanned aircraft systems into the airspace could lead to 100,000 jobs and $82 billion in economic activity. Market projections for urban air mobility are in the billions of dollars.

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While there is much to celebrate in the success of U.S. commercial air transportation, our competitiveness on the global market is increasingly harder to maintain. The International Aviation Transportation Association predicts that by the mid-2020s, "China will displace the United States as the world's largest aviation market." That's why Federal research investments to transform this industry matter, and why we're here today to examine NASA's Aeronautics mission and enabling role. Because maintaining our success and realizing the opportunities before us means overcoming challenges.

Airplane noise complaints to the FAA have seen sharp increases. Growth in air transportation is stretching the capacity of our national airspace system, and new entrants, including drones and urban air vehicles, add complexity to the airspace that must be safely managed if they are to be successful. Perhaps most pressing of all is the impact of air transportation on the environment. Not only does commercial aviation account for about 2% of human-induced global carbon emissions, the jet fuel that produces those emissions represents a significant portion of commercial airline costs. With expected compound annual growth rates of about 3.5 percent in air passengers, the problem will only get worse. Sustainability is not only critical to the environment; it's becoming a competitive advantage.

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In closing, I'd like say this: the proposal for aeronautical research and technology in NASA's fiscal year 1994 budget request was 2 and a half times more in 2019-year dollars than the Administration's proposed investment for NASA's Aeronautics research programs in the fiscal year 2020 budget request. Recognizing the magnitude of the economic impact of U.S. commercial aviation today, and the challenges and opportunities ahead, is it sufficient?

Thank you.

Chairwoman HORN. The Chair now recognizes Ranking Member Babin for an opening statement.

Mr. BABIN. Thank you, Madam Chair, and thank you, witnesses, for being here today. I'm looking forward to hearing what you have to say.

Modern day aeronautics was founded by American ingenuity. And while flying machines were proposed by great minds like DaVinci, and balloons and gliders preceded aircraft, it was two bicycle makers from Ohio that proved, in 1903, that dreams are more than just imagination. They were the first to demonstrate an aircraft with powered flight in Kitty Hawk, North Carolina, which propelled America to the forefront of a new technological revolution. Many were engaged in solving the riddle of flight at the time. Some, like Samuel Langley, were supported by significant government funding, and the backing of established institutions like the Smithsonian. But it was the industrious tinkerers, backed by nothing but their own curiosity, who made the impossible possible.

Wilbur and Orville Wright, as well as many others, went on to proselytize the potential of aviation, and participate in the Nation's first government aviation organization, the National Advisory Committee for Aeronautics, or NACA. Founded in 1915 to supervise and direct the scientific study of the problems of flight, with a view to their practical solution, NACA's roots in aviation formed the foundation for NASA. Those proud traditions continue today in the Aeronautics Mission Directorate.

NASA is currently tackling several technological challenges. They're developing the low boom flight demonstrator to enable commercial supersonic flight that will drastically reduce flight times. They're building off of the success of the X-15, the X-43, and the X-51 to continue research and development into hypersonic flight, which could revolutionize space flight, enable faster transportation, and also promote national security. And while the U.S. has been at the forefront of hypersonic research for decades, Russia and China are making significant progress in this field, which threatens our own national security.

NASA is also supporting urban air mobility, electric aircraft, and air traffic management research to promote innovation, and enable more efficient use of our air space. These are all fascinating fields of study. One aspect of aeronautics research that we must diligently monitor is international competitiveness. And while the U.S. has historically led the world in aeronautics and aviation, this lead cannot be taken for granted.

Other nations are investing significant resources to challenge our leadership, but many of those countries embrace a strategy based on subsidies and government-sponsored monopolies that run counter to the American free-market spirit. And before we adopt policies similar to our international competitors, we should consider whether some technological challenges are best left to the market to solve. After all, it was the Wright brothers' curiosity and drive that made them successful, not government subsidies or political favoritism.

Similarly, when we compare investments in aeronautics made by countries like China to NASA, or the U.S. government's investment, we must realize that virtually all of China's investments are made by the public sector, whereas here in America we have a vibrant private sector that is also investing in our Nation's aeronautics future. Aeronautics and aviation make up a significant portion of our nation's economy. Preserving our leadership role is something that we can all agree on.

I look forward to working with my colleagues on this Committee, and with the Senate, and with the Administration to ensure the future of our aviation economy is just as bright as the past. And I yield back.

[The prepared statement of Mr. Babin follows:]

Modern-day aeronautics was founded by American ingenuity. While flying machines were proposed by great minds like da Vinci, and balloons and gliders preceded aircraft, it was two bicycle makers from Ohio that proved in 1903 that dreams are more than just imagination. They were the first to demonstrate an aircraft with powered flight in Kitty Hawk North Carolina, which propelled America to the forefront of a new technological revolution. Many were engaged in solving the riddle of flight at the time. Some, like Samuel Langley, were supported by significant government funding and the backing of established institutions like the Smithsonian. But it was the industrious tinkerers, backed by nothing but their own curiosity, who made the impossible possible.

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Chairwoman HORN. Thank you very much, Mr. Babin. It's a pleasure to work with you on this Committee, and we're very happy to have such a distinguished panel. And—give us just one moment. Excuse me. OK. Looks like we're waiting on a few people to arrive. If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

[The prepared statement of Chairwoman Johnson follows:]

Thank you, Madame Chair, for holding this hearing on NASA's aeronautics mission and the activities of the Aeronautics Research Mission Directorate.

As most of us in this room know, Aeronautics is the first "A" in NASA. NASA's very origins grew out of the National Advisory Committee for Aeronautics (NACA), which was established nearly 105 years ago to advise the nation during World War I and to advance U.S. aviation in light of Europe's rapid advancements. NACA's foundational research, experiments, flight tests and simulations not only established the U.S. aviation industry, it made possible the nation's early work in aeronautics and spaceflight.

Today, over 100 years later, the importance of aeronautics to the nation has only grown. As Chairwoman Horn noted in her opening statement, the economic value of both existing commercial air transportation and emerging markets is significant, as are the innovative technologies and new operations on the horizon. This innovation is happening around my own District in Dallas, which will be one of the cities in which urban air mobility is to be tested.

Yet there are many challenges in realizing opportunities such as urban air mobility. Noise, public acceptance, safety, and the integration of new, and eventually autonomous, systems into the national airspace are just a few. Research is needed to address these challenges, reduce risks, and enable the industry to lead in these emerging areas of civil aviation.

Our investments in NASA's Aeronautics Research Mission Directorate have already returned handily in the infusion of NASA Aeronautics research into commercial and military aircraft, and in demonstrating tools for more efficient air traffic management that are being transitioned to the FAA for operational use, for example.

While the economic impact of civil and commercial aviation is truly impressive, we can't take for granted the fact that other nations are becoming increasingly capable. The global market is competitive. Our ability to sustain our leadership and realize future opportunities in civil and commercial aviation require R&D investments and people.

As Chairwoman Horn noted, in Fiscal Year 1994, the Administration's request for aeronautics research would be the equivalent of $1.76 billion in 2019-year dollars, after accounting for inflation. That's 2-1/2 times more than the Fiscal Year 2020 budget request for NASA's research aeronautics activities. And while the comparison may not be exact in the programmatic content included, the contrast is nonetheless very concerning. If we under-invest in research that supports one of the only industries in the nation that has a positive trade balance, provides for high-paying, skilled jobs, and has an economic impact for the U.S. economy of more than a trillion dollars, we risk losing the very tax base and national revenue that will help us support NASA and the broader R&D activities in our Federal government.

I look forward to working with the Chairwoman and Ranking Member of the Subcommittee, the Ranking Member of the Full Committee, NASA, industry, and academia in considering the investments needed to ensure that NASA's aeronautics research, facilities, and workforce are positioned to enable the transformation in aviation that we are discussing today.

Thank you, and I yield back.

Chairwoman HORN. And now I would like to take a moment to introduce our witnesses today.

Our first witness is Dr. Jaiwon Shin, Associate Administrator of NASA's Aeronautics Research Mission Directorate, where he has the responsibility for the strategic direction and management of NASA's aeronautics research portfolio. Dr. Shin also co-chairs the National Science and Technology Council's Aeronautics, Science, and Technology Subcommittee. Dr. Shin has served on many—in many positions in NASA, including as Chief of Aeronautics Projects Office at NASA's Glenn Research Center. Dr. Shin received a bachelor's degree from Yonsei University in South Korea, and a master's degree from California State University, Long Beach, and a doctorate in Mechanical Engineering from Virginia Polytechnic Institute and State University. Welcome, Dr. Shin.

Our second witness is Dr. Alan Epstein. Dr. Epstein is the R.C. Maclaurin Professor of Aeronautics and Astronautics Emeritus, and is the former Director of Gas Turbine Laboratory at the Massachusetts Institute of Technology (MIT). Previously Dr. Epstein was the Vice President of Technology and Environment at Pratt and Whitney, an aerospace manufacturing company. Dr. Epstein is the Chair of the National Academies of Aeronautics and Space Engineering Board, and is a member of the NASA Advisory Council. Dr. Epstein is a member of the U.S. National Academy of Engineering, and past Chair of its aerospace section. Dr. Epstein received his bachelor's, master's, and doctorate degrees from the Massachusetts Institute of Technology. Welcome, Dr. Epstein.

Our third witness today is Dr. Ilan Kroo, the Thomas V. Jones Professor of Aeronautics and Astronautics, and Director of the Aircraft, Aerodynamics, and Design Group at Stanford University. Previously Dr. Kroo served as the founding CEO of Zee.Aero, now Kittyhawk, and E-VTOL—did I do that right? I didn't do it quite right. You can correct me later—Manufacturing Company. Dr. Kroo is currently a member of the National Academies of Aeronautics and Space Engineering Board, and is on the American Institute of Aeronautics and Astronautics, Aircraft Design Technical Committee. Dr. Kroo is a member of the U.S. National Academy of Engineering, and received his bachelor's, master's, and doctorate degrees from Stanford University. Welcome, Dr. Kroo.

Our fourth and final witness is Dr. Mark Lewis. Dr. Lewis is the Director of the IDA Science and Technology Policy Institute. Dr. Lewis also served as the Willis Young, Junior Professor and Chair of the Department of Aerospace Engineering at the University of Maryland. Previously Dr. Lewis was President of the American Institute of Aeronautics and Astronautics, and served as an advisor in the Air Force. Dr. Lewis is a member of the National Academies of Aeronautics and Space Engineering Board. He received his bachelor's, master's, and doctorate degrees from the Massachusetts Institute of Technology. Welcome, Dr. Lewis. You'd think that MIT might know a thing or two about aerospace, aeronautics, based on this.

As our witnesses, you should know that you each have 5 minutes for your spoken testimony. Your written testimony will be included in the record for the hearing. And when you've completed your spoken testimony, we'll begin with questions. Each Member will have 5 minutes to question the panel. And we will start today with Dr. Shin. Dr. Shin, you're recognized for 5 minutes.

TESTIMONY OF DR. JAIWON SHIN, ASSOCIATE ADMINISTRATOR, AERONAUTICS RESEARCH MISSION DIRECTORATE, NASA

Dr. SHIN. Thank you, Madam Chair, Ranking Member Babin, and Members of the Subcommittee. I really appreciate to have this opportunity to discuss FY 2020 budget request for NASA Aeronautics Research Mission Directorate. I would like to thank you for your continued support of the groundbreaking work good women and men in NASA Aeronautics are performing. Aviation is fundamental to the future of U.S. economy. NASA's cutting-edge aeronautics research is delivering new concepts and technologies, boosting U.S. global leadership, and creating high-quality jobs. Growing consumer demand, combined with innovative technologies and disruptive thinking, is transforming aviation in ways we could hardly imagine just a few years ago.

Since 1973, commercial supersonic flight has been banned over land in the U.S. and around the world due to concerns of sonic boom. Over the past 10 years or so, NASA has developed technologies that will greatly reduce sonic boom noise. With support from the Congress, NASA is now building a quiet supersonic experimental aircraft, X-59 Quest, with a commitment for first flight by Fiscal Year 2022. Once built, NASA will measure public response to the sonic boom noise, and deliver the data to the FAA and the International Civil Aviation Organization to enable new rules allowing commercial supersonic flight over land, which will spark U.S. aviation industry's innovation and investment to take the global leadership position in developing future commercial supersonic airplanes.

Subsonic aircraft will still carry the majority of passengers in the foreseeable future, but demands for reduced fuel burns, noise, and emissions are growing rapidly. NASA is collaborating with U.S. industry to develop innovative technologies, such as efficient wing designs, electric propulsion, and transformative materials and structures. Hybrid electric, or all electric propulsion, is being explored by aviation industry to bring dramatic reductions in fuel burns and emissions for future aircraft. NASA has been—NASA has begun a multi-year effort to enable one megawatt power electric propulsion system, which defines a critical technological milestone for electrification of aircraft, stirring notable international competition. Realizing an aviation grade one megawatt propulsion system has never been accomplished. NASA has built a world-leading ground test facility called NASA Electric Aircraft Test Facility, or NEAT, and we are already conducting a test of a high power electric propulsion system with our industry partner.

The change to the aviation system also requires changing the way air traffic is managed. NASA has been developing innovative technologies to enable highly efficient air traffic management systems, while maintaining safety by collaborating with the FAA, airlines, and airport operators. Once such example is a new integrated surface management capability NASA is developing which will enable aircraft to move from the gate to take off without stops—any stops and waits. Our collaboration with FAA and operators at Charlotte International Airport has already saved 1.6 million pounds of fuel, and reduced emissions equivalent to over 57,700 trees in just the first 15 months of trials. FAA plans to deploy this technology to 27 of the Nations' biggest airports beginning in 2021.

Increased use of autonomous systems is opening up completely new markets, such as commercial drone industry. NASA's research into UAS (unmanned aircraft systems)—communication and air traffic management has served as a critical enabler of the industry that did not exist only a few years ago. For example, under NASA's leadership, the most complex demonstration of the UAS traffic management, or UTM system in downtown Reno, Nevada, is scheduled to end the 10-day flight test tomorrow with great success. NASA has conducted four major capability demonstrations, including this one, in the last 4 years, which provided to be critically important steps toward enabling safe, efficient commercial flights of small UAS in dense urban environments. Just as a brand new drone industry is blossoming, another exciting industry called urban air mobility, or UAM, is emerging. Without NASA's only work in small UAS, a vision to open the skies over our communities, to move people and cargo safely, would not have been even conceivable. NASA is closely working with new industry—this new industry to rapidly develop key capabilities, such as reducing noise, and ensuring safety of our vehicles.

The global aviation system of mid-21st century is emerging today. NASA Aeronautics strengthen the foundation of U.S. global leadership by working with traditional and emerging market players to bring exciting future for aviation. Thank you for this opportunity to testify today, and I look forward to answering any questions you may have.

[The prepared statement of Dr. Shin follows:]

HOLD FOR RELEASE UNTIL PRESENTED
BY WITNESS
June 26, 2019

Statement of

Jaiwon Shin, Ph.D.
Associate Administrator for Aeronautics Research Mission Directorate
National Aeronautics and Space Administration

before the

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

Chair Horn, Ranking Member Babin, and Members of the subcommittee, I am pleased to have this opportunity to discuss the FY 2020 budget request for NASA's Aeronautics Research Mission Directorate (ARMD). I would like to thank you for your continued support of NASA and the groundbreaking work we are doing in ARMD. We are at a pivitol point within the agency as we focus on important programs and projects like Artemis agency-wide, and commercial supersonic flight, electric propulsion and Unmanned Aerial Systems integration among others within ARMD.

I mentioned Artemis. Artemis is the name of NASA's lunar exploration program that will send the first woman and the next man to the South Pole of the Moon by 2024 and develop a sustainable human presence on the Moon by 2028. Artemis takes its name from the twin sister of Apollo and goddess of the Moon in Greek mythology. Our hope is that this program, and the full complement of NASA missions will serve to inspire the Artemis generation to continue to explore, discover, and achieve.

NASA is working to build a sustainable, open architecture that returns humanity to our nearest neighbor. We are building for the long term, utilizing the Moon as a proving ground for humanity's first crewed mission to Mars. We are intending to design an open, durable, reusable architecture that will support exploration for decades to come. Sustainability requires reusable systems and partnerships from across the commercial sector and around the world. Robotic scientific missions delivered by commercial landers will be the first Artemis elements to land on the Moon. NASA is completing development of both the Orion spacecraft that will carry humans to lunar orbit, and the Space Launch System (SLS) rocket that will launch Orion.

We have capitalized on commercial, industry, international and university partners to advance aeronautics research to support design, technology and safety. We will continue to apply these partnerships in the Artemis program to incentivize the best in these areas for exploration.

Aviation moves the world, and an efficient and safe air transportation system is fundamental to the future of the U.S. economy. NASA's cutting-edge aeronautics research is delivering new concepts and technologies that will change the face of aviation as we know it, boosting U.S. technological and economic leadership in this global industry and creating high quality American jobs. Growing consumer demand, combined with development of innovative technologies and disruptive thinking are leading to transformation of the aviation sector in ways we could hardly imagine just a few years ago.

Aviation generates $1.6 trillion in total U.S. economic activity a year, and contributes about 5 percent of the U.S. Gross Domestic Product.[1] Aviation in the U.S. supports 10.6 million direct and indirect jobs,[2] and generates the largest positive trade balance of any manufacturing sector, over $84.8 billion per year.[3]

Tomorrow's aviation system will change the world. People and packages will move more quickly, and in new ways. Tomorrow's aviation system will still be safe and efficient, but now much more widely accessible to all citizens. Aviation enables new ways of living, working and connecting with others. Exciting new technology and changing consumer demand will change our relationship with aviation. Today's explosion of new business models for ground transportation (such as ride sharing and package delivery) is taking to the air, enabling an entirely new aviation mobility market and opportunity space for tomorrow.

These trends are real. Innovation and growing global economies will double global passenger air travel in the next twenty years as new products are introduced. Air travel will expand as economies grow and develop.[4] Boeing predicts demand of 42,730 new aircraft in the next twenty years and a market worth over of $6 trillion.[5] According to Airbus, there will be another $3 trillion in aftermarket services needed in that time period.[6] High speed flight – faster than the speed of sound – will open up new routes and new opportunities for air travel around the world.

This growth in aviation means jobs. Boeing has projected that aviation will need 790,000 new pilots by 2037 to meet growing demand, with 96,000 pilots needed to support the business aviation sector.[7] There will be similar growth in jobs for manufacturing, technicians, and aviation services, as well as new jobs created as a result of new economic opportunities..

Global competition is fierce in this sector as companies and countries seek to capture a larger share of this growing market and high wage jobs. U.S. and European companies traditionally

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1 The Economic Impact of Civil Aviation on the U.S. Economy," Federal Aviation Administration, November 2016, Page 20, PDF

2 The Economic Impact of Civil Aviation on the U.S. Economy," Federal Aviation Administration, November 2016, Page 20, PDF

3 The Economic Impact of Civil Aviation on the U.S. Economy," Federal Aviation Administration, November 2016, Page 20, PDF

4 2036 Forecast Reveals Air Passengers Will Nearly Double to 7.8 Billion," International Air Transport Association, October 24, 2017, Web Page

5 https://www.boeing.com/commercial/market/commercial-market-outlook/

6 https://www.airbus.com/newsroom/press-releases/en/2016/07/airbus-forecasts-3-trillion-commercial-aviation-aftermarket-services-over-the-next-20-years.html

7 https://www.boeing.com/commercial/market/pilot-technician-outlook/2018-pilot-outlook/

have divided the global market for large civil aircraft and equipment. Now China is investing heavily in aerospace, starting up a new company to build large commercial aircraft to lure some of the large civil aircraft market share. Russia and Japan are seeking to break into the regional jet market, and companies from all around the world are seeking market share for smaller unmanned systems and vehicles.

NASA Aeronautics is uniquely positioned to be the catalyst for this exciting future, and to ensure that the U.S. maintains a strong leadership role. We have been a global leader in creating and realizing amazing advances in aviation for generations, developing new technologies and new concepts for how the aviation system can be better, faster, and more efficient. NASA Aeronautics research has been incorporated into nearly every aircraft flying today. The United States has the safe, global air transportation system we have today in part because of NASA research.

NASA's research today in areas such as composite materials, new airplane concepts, air traffic management, and safe routine integration of unmanned aerial systems (UAS) into the National Air Space is forging the path to the future of aviation.

NASA works with U.S. aviation community and government partners to create opportunities for American businesses, raising the level of performance for all participants. NASA has a vision for what is possible, based on deep insight into the goals and needs of the aviation community and U.S. industry engagement early in the technology development cycle. We invest in aeronautics research to address the most critical challenges, always with an eye toward the practical application of the results. We bring the most promising technologies to flight to demonstrate them in a realistic environment, in collaboration with our U.S. industry partners whenever appropriate. Partners leverage NASA's investments through joint efforts that complement the agency's internal capabilities, provide access to a wide range of technologies beyond the traditional aeronautics portfolio, and facilitate technology transfer to more mature states of development and eventual implementation.

One critical government partner to NASA is the Federal Aviation Administration. We work closely with FAA leaders and technical experts to ensure our research meets their long term needs, and the results of our research can be transitioned and inform their investment decisions. Our successful model for collaboration is embodied in Research Transition Teams (RTTs), which are designed to develop technology for NextGen advancements in critical areas and effectively transition advanced capabilities to the FAA for certification and implementation. RTTs serve as the bridge between NASA's long term technology R&D, and FAA's near term R&D to support implementation and certification of new technologies and systems. Under RTTs, NASA and FAA develop joint research plans and fund their respective portions of the planned research according to the nature of the research, stage of research, and their relative capabilities. Data from our research results are used to develop standards and regulations through rulemaking committees and domestic and international standards bodies.

To achieve our future vision for aviation, NASA is investing in discovery of new concepts and technologies in a few key areas.

Routine supersonic passenger travel will enable passengers to make current long journeys into day trips. However, current rules prohibit supersonic flight over land, a reaction to the public's objection to noisy supersonic Concorde flights in the 1970s. Over the past decade, NASA fundamental research and experimentation has demonstrated the possibility of supersonic flight with greatly reduced sonic boom noise, but the rules prohibiting over-land supersonic flights remain. In order for this sector to take off, regulators need proof that the public will accept these quieter supersonic flights. NASA now is building a quiet supersonic experimental aircraft – X-59 QueSST – to provide this proof, with a commitment for first flight by FY 2022.

Once built, NASA researchers will measure public acceptance of the technology by flying the X-59 over a handful of U.S. cities. This data will be delivered to the Federal Aviation Administration and the International Civil Aviation Organization to support the development of new rules allowing commercial supersonic flight over land. This capability will position the U.S. aviation industry to supply global customers with future supersonic aircraft products.

Subsonic aircraft will still carry the majority of passengers in the foreseeable future, but those aircraft most likely would be different from today. Large leaps in aircraft efficiency coupled with reductions in noise and harmful emissions are critical to the environmental sustainability of aviation. Through technical advances by NASA and industry in the coming years, it is likely that future aircraft may look different, may be made from different materials, may be powered differently, and may even be designed and manufactured differently.

NASA is collaborating with U.S. industry to investigate innovative technology for subsonic aircraft such as advanced configurations and wing design, transformative structures, propulsion-airframe integration, and small core turbine engines.

NASA also is leading research into new components, technologies and powertrain architectures for electric or hybrid electric systems that can bring about revolutionary improvements in small and large transport aircraft. NASA's research on developing an all-electric, general aviation size experimental airplane – the X-57 Maxwell – already is delivering to the community important lessons about designing, building and operating an all-electric system. Ground tests this year and flight tests next year will provide valuable insights into the challenges and opportunities of electric aircraft and serve as the building blocks for industry to create future safe and certifiable aircraft designs.

NASA recently completed single-aisle transport aircraft concept studies with industry to develop hybrid gas-electric propulsion concepts and assess the potential benefits for larger vehicles such as regional transports and airplanes as large as a Boeing 737.

Building on these activities, NASA has begun a multi-year effort to solve the technical challenges of a 1-Megawatt (MW) power electric propulsion system – enough energy to power 165 homes. NASA will refine concepts and technologies and validate new electric systems through ground and flight tests. A shift to hybrid-electric or all electric propulsion from modern turbofan engines could yield a significant fuel savings, with a dramatic impact on airline operating costs. Realizing a practical 1-MW electric propulsion system has never been accomplished and is an area of notable international competition. To support this work, NASA has commissioned a world-leading NASA Electric Aircraft Test Facility (NEAT) capable of conducting full scale ground test of high-power electric propulsion systems.

Future aerospace design and manufacturing processes will be more efficient, reducing the time and cost required to build aircraft. Future computational design and certification capabilities of advanced materials required for emerging aeronautical vehicle applications are identified in NASA's "Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation" report and the CFD 2030 report. Next year, NASA will complete the Advanced Composites Project, a six-year focused effort with industry to significantly reduce the time needed to develop and certify new composite structures for aerospace applications.

Autonomy and increased automation bring new opportunities to do the things we already do even better, but also hold the potential to open new markets and create new benefits that are not yet possible. In 2020, NASA will complete demonstrations of technologies to integrate operations of larger Unmanned Aircraft Systems (UAS) in the existing National Air Space (NAS) as well as manage smaller UAS vehicles safely at lower altitudes.

NASA recently completed the most complex demonstration yet of the UAS Traffic Management System or UTM in Reno, Nevada. These demonstrations are proving that the UTM concept can safely and efficiently manage flights of small UAS in dense urban environments, and represent an important step toward commercial adoption of the UTM concept.

Those efforts are providing the foundation for another major transformation of the aviation sector being led by NASA – creation of an urban air mobility or UAM system that is safe, economical and environmentally friendly to move people and packages in population centers, forever changing how citizens around the world benefit from aviation. UAM vehicles can range from small delivery drones to passenger-carrying air vehicles that have electrically-powered Vertical Take Off and Landing (eVTOL) capability.

NASA will begin a new Advanced Air Mobility project in FY 2020 to enable the emergence of UAM. NASA is preparing a series of "Grand Challenges" that will provide a means to assess the maturity of key systems for Urban Air Mobility. Through these Grand Challenges, NASA will serve as a catalyst for companies to rapidly develop and demonstrate their capabilities, while setting the course for research and investment needed to realize the full potential of UAM. Research to reduce noise and improve efficiency and safety of vertical lift vehicles also is supporting development of this fledgling industry. The initial aerospace community response to NASA's leadership in UAM has been strongly supportive.

NASA research is enabling a transformed airspace system that supports efficient operations of all vehicles across these different market segments, and gives citizens the confidence that every flight is safe and secure. NASA will complete a series of Airspace Technology Demonstrations (ATDs) with the FAA, airlines and airport operators to demonstrate new capabilities for managing efficient airline operations.

The most recent trials at Charlotte airport for ATD2 are demonstrating an Integrated Arrival and Departure and Surface (IADS) management capability, which enables precision gate push back, allowing commercial airplanes to execute a non-stop taxi for take-off and continuous climb to an available overhead stream slot. These integrated capabilities have already yielded benefits for demonstration participants, equal to 2.1 million pounds of fuel saved and an emissions reduction equivalent to over 77,000 urban trees in just the first 19 months of the demonstration. This work has all been coordinated through the NASA-FAA ATD Research Transition Team, such that the ATD-2 demonstration directly influenced requirements and reduced risk for FAA's $1 billion Terminal Flight Data Manager (TFDM) Program which will deploy IADS capabilities to 27 airports beginning in 2021.

A final high-fidelity demonstration of integrated system capabilities will support delivery of the research and development results to the FAA to advance NextGen capabilities and improvements to meet the FAA's air traffic needs. NASA then will turn its attention to new research to address the safety and efficiency challenges of a more complex airspace supporting a broad range of new users.

Beginning in FY 2019, NASA increased its support of unique specialized facilities and experts who conduct fundamental research to address key challenges in hypersonic flight by $5 million, a twenty percent increase above FY 2018. NASA coordinates closely with partners in the Department of Defense (DOD) to leverage DOD investment in ground and flight activities to develop and validate advanced physics-based computational models as building blocks towards a long-term vision for hypersonic flight. At the same time, the DOD benefits from NASA hypersonics expertise, analyses, testing capabilities and computational models.

The global aviation system of 2040 is emerging today – new companies and new systems built on advanced technologies pioneered by NASA and strengthened by steady U.S. investment. NASA Aeronautics strengthens the foundation of U.S. global leadership in both traditional and emerging markets to realize the 2040 aviation system. To do this, NASA Aeronautics will:

- Develop and demonstrate key enabling technologies in close partnership with the U.S. aviation industry to transform the subsonic airliners market, with particular focus on electric or hybrid electric systems that can bring about revolutionary improvements in small and large transport aircraft.
- Develop and demonstrate key enabling technologies in full partnership with the Urban Air Mobility community to ensure U.S. leadership in opening a scalable, safe, efficient, and environmentally acceptable market. This new capability will reduce ground-based traffic congestion, improve local air quality, and transform urban areas.
- Deliver scientifically acquired data of sonic boom community response to the international and U.S. standard and rule making organizations (e.g., ICAO, FAA) to usher in renewed supersonic flight for the flying public.
- Complete a series of air traffic management technology demonstrations with the FAA, airlines, and airports that validate new capabilities that improve the National Airspace System (NAS) efficiency. Also, NASA will complete demonstrations of technologies to integrate larger UAS into the NAS as well as manage smaller UAS at lower altitudes.

Thank you for the opportunity to testify before you today. I welcome any questions you may have.

National Aeronautics and Space Administration

Biography

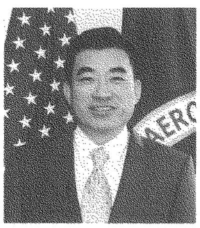

Image Credit: NASA/Maria Werries

Dr. Jaiwon Shin

Associate Administrator
NASA Aeronautics Research Mission Directorate (ARMD)

Dr. Jaiwon Shin is the associate administrator for the Aeronautics Research Mission Directorate (ARMD), a position which he has held since 2008. Shin manages the agency's aeronautics research portfolio and guides its strategic direction, including research in advanced air vehicle concepts, airspace operations and safety, integrated aviation systems, and the nurturing and development of transformative concepts for aviation.

Shin co-chairs the National Science & Technology Council's Aeronautics Science & Technology Subcommittee whose charter is to facilitate coordination and collaboration among the federal departments and agencies that fund aeronautics-related research. The subcommittee wrote the nation's first presidential policy for aeronautics research and development (R&D). The policy was established by Executive Order 13419 in December 2006 and will guide U.S. aeronautics R&D programs through 2020.

He is a past chair of the International Forum for Aviation Research, the world's only aviation research establishment network, with 26 member countries that seeks to connect research organizations and enable information exchange on aviation challenges of common interest.

Between May 2004 and January 2008, Shin served as deputy associate administrator for the ARMD, where he was instrumental in restructuring NASA's aeronautics program to focus on fundamental research and better align with the nation's Next Generation Air Transportation System (NextGen).

Prior to coming to work at NASA Headquarters, Shin served as chief of the Aeronautics Projects Office at NASA's Glenn Research Center. In this position he managed all of the center's aeronautics projects. Prior to this, he was Glenn's deputy director of aeronautics, where he provided executive leadership for the planning and implementation of Glenn's aeronautics program, and interfaced with NASA Headquarters, other NASA centers, and external customers to explore and develop technologies in aeropropulsion, aviation safety and security, and airspace systems.

Between 1998 and 2002, Shin served as chief of the Aviation Safety Program Office, as well as the deputy program manager for NASA's Aviation Safety Program, and Airspace Systems Program. He assisted both program directors in planning and research management.

Biography

Dr. Jaiwon Shin (continued)

Associate Administrator
NASA Aeronautics Research Mission Directorate (ARMD)

His NASA honors include the 2008 Presidential Rank Award for Meritorious Senior Executive, NASA's Outstanding Leadership Medal, NASA's Exceptional Service Medal, a NASA Group Achievement Award, Lewis Superior Accomplishment Award, three Lewis Group Achievement Awards, and an Air Force Team Award.

In 2019, Shin was honored as a Fellow by the AIAA, a distinction that is conferred upon individuals in recognition of their notable and valuable contributions to the arts, sciences, or technology of aeronautics and astronautics. He is a recipient of the 2017 AIAA Laureate Award for Innovation, and an Office of Personnel Management 2016 Meritorious Presidential Rank Award. He is a graduate of the Senior Executive Fellowship Program at the Kennedy School of Government at Harvard University, has extensive experience in high-speed research and aircraft icing, and has authored or co-authored more than 20 technical and journal papers.

Shin received his doctorate in mechanical engineering from the Virginia Polytechnic Institute and State University, Blacksburg, Virginia. His bachelor's degree is from Yonsei University in Korea and his master's degree is in mechanical engineering from the California State University, Long Beach.

Chairwoman HORN. Thank you, Dr. Shin. Dr. Epstein?

TESTIMONY OF DR. ALAN H. EPSTEIN, R.C. MACLAURIN PROFESSOR EMERITUS OF AERONAUTICS AND ASTRONAUTICS, MIT, AND CHAIR, AERONAUTICS AND SPACE ENGINEERING BOARD, NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE

Dr. EPSTEIN. Madam Chair, Ranking Member Babin, Members of the Subcommittee, I am please to address NASA's role in aviation. I believe that we are living in the most exciting era for aviation in the last 50 years. Opportunities include ultra-quiet flight, true air taxi service, and low boom supersonic travel. Challenges include environmental concerns, rising foreign competition, and, of course, safety. Adding to the excitement are new entrants backed by venture capital, many of whom are outside the U.S.

Government should care because the U.S. owns 49 percent of the world's $800 billion-a-year aerospace business. Other countries understand the importance of this market, and are making concerted attacks. First Europe with Airbus, and now China. To no small degree, NASA Aeronautics holds stewardship of this Nation's aeronautical future. Let me point out that shortly after the turn of the century the Aeronautics budget was cut by more than half in terms of operational funds. So, for the past 2 decades, Aeronautics has made due with relatively modest resources.

I would now like to touch a few areas in which NASA can have significant impact. For example, the X-59 airplane will validate the concept that airplane shape can dramatically reduce sonic boom. This aircraft will then generate data from cooperating communities on peoples' tolerance for low intensity booms. This will provide a foundation to the FAA to re-examine its ban on over-land supersonic flight, and help them work with the international community to set certification standards for supersonic aircraft.

A second is urban air mobility. Air taxis have been a dream since the 19th century. Such vehicles are now technically feasible. Public acceptance requires very low noise, and close to accident-free operation, areas of NASA's strength. More challenging is the need to safely integrate large numbers of these new vehicles into our crowded airways. NASA has an important technology role to play here as well.

Now I'd like to touch on a topic for which I'm passionate, airplane noise. As we all know, community noise is a major irritant. People simply don't want airport noise. Progress in noise reduction has now reached the point where I believe we can envision aircraft so quiet that they would not be noticed in an urban environment. Virtually silent airliners would bring enormous relief to communities, and stimulate an expansion of air travel. With aggressive NASA action, I believe that such ultra-quiet airliner technology could be ready by the end of the next decade.

Last, I would like to address climate change's threat to aviation. Some have misidentified aviation as a major factor in global warming, and so even attack the idea of flying. For example, the Bishop of London declared vacation flying a sin, and flight shaming is growing in Scandinavia. In fact, modern airplanes produce less CO_2 per passenger mile than do cars and trains in this country. Nevertheless, the threat is real. In response, industry leaders pledge to halve aviation CO_2 by 2050. Such progress requires reducing the energy needed for flight, and the fossil carbon of that energy. More than 98 percent of aviation CO_2 comes from large aircraft flying distances more than 500 miles, so significant reduction requires focusing on airliners, not general aviation or small regional aircraft.

Also, we now understand that aviation can't follow the auto industry in moving toward battery-powered vehicles. There's no battery technology on the horizon suitable for large electric airliners. Even if a breakthrough enabled battery power, it would make things worse rather than better, because modern engines produce less CO_2 per unit of power than does the Nation's power grid, and will likely do so for the next several decades. NASA's work on energy reduction should focus on efficient aircraft and engines.

In summary, this is an extraordinarily exciting time for aviation. Civil aeronautics is a major economic strength of the United States, and a strong NASA Aeronautics is needed to maintain that strength. The leadership and support that NASA provides is important at all levels. Supporting students in basic university research, stimulating new concepts, and exploring technology at larger scales, as with X planes. Thank you.

[The prepared statement of Dr. Epstein follows:]

Testimony before the Committee on Science, Space, and Technology
U.S. House of Representatives

Hearing on NASA's Aeronautics Mission: Enabling the Transformation of Aviation
June 16, 2019

Statement of
Dr. Alan H. Epstein
R.C. Maclaurin Professor Emeritus
Massachusetts Institute of Technology,
Chair of the Aeronautics and Space Engineering Board
of the National Academies of Science, Engineering, and Medicine

Madam Chair, Ranking Member Babin, and members of the subcommittee, thank you for the opportunity to testify today. I am Alan Epstein, the RC Maclaurin Professor Emeritus at MIT, Chair of the Aeronautics and Space Engineering Board of the National Academies of Science, Engineering, and Medicine, and a member of the NASA Advisory Council. I am here to address this nation's aeronautical enterprise and the role that NASA can and should play. I speak today as an individual, not for any organization.

I believe that we are living in the most exciting era in civil aviation in 50 years, essentially since the development of the Boeing 747. As is often the case, the excitement stems both from opportunities and from challenges. Opportunities now include dramatic reductions in aircraft noise, drones of all sizes and shapes, true air-taxi service, and low-boom supersonic travel. Challenges include environmental concerns, especially those associated with climate change; the rise of foreign competition; refreshing our talent pool; and, of course, safety. An additional element of the excitement is that many of the opportunities are being pursued by wholly new entrants rather than the few traditional, large aerospace companies. Many of the new entrants are based outside the U.S., and many have considerable resources from venture capitalists.

What is the proper government role in all of this? Why should the American people and Congress care? Fundamentally, it is because aerospace is very big business, and it is very much an American business. Not including airline operations, aerospace is a more than 800 billion dollars a year worldwide enterprise, with the US responsible for 49% of that total. In 2017 alone, about 180 billion dollars of new aircraft were delivered, of which almost 80% were civil aircraft. Aircraft maintenance, repair, and overhaul add another 130 billion dollars annually. Civil aerospace employs about half a million people in the US. Aerospace products combined are the largest net export of the US (and it should be noted that complete aircraft account for less than half of this total; the majority is components - engines avionics, landing gear and brakes, and so on). All-in-all, civil aerospace is a vital, vibrant segment of our economy.

Other countries recognize the importance of this market and have made concerted attacks on US leadership through government investment. We have lost unquestioned leadership in helicopters, the US military now flies European designs, Airbus has been extraordinarily successful in the airliner business, and China is making large investments to enter and the capture market. To no small degree, NASA Aeronautics holds stewardship of this nation's civil aeronautical future and it is essential to that future that its research is appropriately supported.

Historically, NASA Aeronautics' research activities and influence have spanned the entire range from basic science to large scale demonstrations. It is the principal funder of university aeronautical research and supports the students that are this nation's aeronautical future. NASA researchers partner with universities and industry to stimulate and pursue new ideas and concepts. Many of the widely used aeronautical design codes of today had their origin at or with NASA. Widely used technologies such as winglets originated in NASA research, as did many, many less visible examples inside airplanes and engines. Also, NASA is responsible for much of the nation's sizable aeronautical research and development tools such as wind tunnels and test facilities.

NASA occupies a unique position in the nation's aeronautical enterprise. It is both a funder and an executer of research. It originates or the funds new ideas and has the where-with-all to shepherd concepts to the point that an industrial enterprise can plan product development. How much of this activity is performed or funded by NASA varies widely. I would like to touch on a few areas in which NASA investment have, can, or should have significant impacts.

First, let me point out that shortly after the turn of this century, a decision was made to dramatically cut the NASA Aeronautics budget, by more than half in terms of operational funds. The budgets of the last decade or two has remained steady at that low level, even with Congressional help. So, NASA has been able to do much in civil aeronautics with what really is relatively little resources.

One current example of a NASA activity which advances US aviation and which I believe to be both appropriate and useful is the X-59 airplane research program. This nation has spent decades researching supersonic flight. One new discovery by NASA was a basic theory predicting that an airplane could be shaped in such a way to dramatically reduce its sonic boom as perceived on the ground. The X-59 is designed to validate this theory. The X-59 will then be used to generate data from cooperating communities on their residents' tolerance for these new low-intensity booms. This data will provide a foundation to enable the FAA to reexamine its ban on overland supersonic flight. Currently, there are no international certification standards for supersonic civil aircraft. This lack of standards is impdes significant corporate investment. Data from the X-59 program can aide the FAA's work with the international community to set data-based standards for supersonic civil aircraft.

A second example is personal air vehicles, an area generating much excitement and investment. While referred to as Urban Air Mobility (UAM), I believe this to be a misnomer since many of the benefits from such aircraft will accrue to suburban and rural communities. Air-taxis have been a dream since the late 19th century. The 20th century was littered with enthusiastic but unsuccessful attempts at flying cars and the like. The present excitement is fueled by the confluence of two maturing technologies – great computational power and enhanced navigation that enable autonomy, and electric-hybrid propulsion that facilitates vertical flight without the mechanical complexities and associated costs of traditional helicopters.

Personal air vehicles have the potential to transform parts of our transportation system. For such aircraft to become wide spread, public acceptance will first require very low noise and close to accident-free operation. NASA can certainly help here given its low noise expertise and interest in safe electric propulsion. Second, the most challenging task may be the requirement to integrate these air-vehicles, along with large numbers of drone, into the national air navigation system. Our airways are crowded now, so the enormous expansion predicted will require new technology and new approaches. While the operation of the air traffic control system is the responsibility of the FAA, NASA has, can, and must contribute significantly to the underlying technology for this effort to be successful.

UAM is by no means a US-dominated business. When last I looked, over 300 companies stated they there were working on UAM, and that doesn't include those working only on drones. Most of these 300 are not in the U.S. and many of the test sites are overseas as well. NASA can help the U.S. capture this market both by pursuing pre-competitive technology developments and by providing the aeronautical depth that some startups lack. NASA is also learning how to work with companies that don't have the patience and breadth of large aerospace firms.

Now, I would like to touch on a topic for which I am passionate, airplane noise. Noise has been a challenge from the beginning of aviation. As we all know noise is a major irritant to the communities around airports and therefore it is a significant impediment to the expansion of our air transportation network. People just do not want new or expanded airports near them. Historically, engines were the dominant noise source, so NASA and industry worked hard for many decades to reduce engine noise. They have made impressive progress. Now, the noise from a modern airliner the size of a Boeing 707 impacts about one tenth the area on the ground and thus one tenth the number of people than did the 707's. In fact, modern engines are so quiet that if you turned the engines off on approach to landing, people on the ground would not hear a difference. The engines are now quieter than the airframe.

While NASA still works on noise reduction, I believe that this is an area where much more can and should be done to the great benefit of this nation. Technology investments to date have brought us to the point where we can envision airliners so quiet that they would not be noticed in an urban environment. Such aircraft will likely look much different than the legacy designs of today so an X-plane research program may well be needed. By that, I mean NASA's flying a special purpose research vehicle to provide data on fundamental technologies that can enable quiet flight. Virtually silent airliners would bring enormous relief to communities around the country and stimulate an expansion of U.S. air transportation. With aggressive NASA action, I believe that such ultra-quiet airliners could be ready to enter service by the end of the next decade.

Lastly, I would like to address aviation's most pressing challenge and opportunity, climate change. Climate change and its political ramifications constitute a significant threat to air transportation. Many people and nations are concerned with anthropogenic drivers, especially CO_2. Some have misidentified aviation as major part of the problem and so attack even the idea of flying. For example, The Bishop of London declared vacation flying "a sin" and "flight-shaming" is growing in Scandinavia. In fact, modern aircraft produce less CO_2 per passenger mile than do cars and trains in this country. Never-the-less, the threat is very real indeed. A decade ago, in response to this concern, aviation leaders pledged to reduce aviation's CO_2 by half by the year 2050. Given that air travel is growing by 4 to 5 percent a year, this is no easy challenge.

The aeronautical technology side of the challenge needs NASA leadership. In house and in-partnership with industry and university researchers, NASA has pursued some very advanced airliner designs which promise significant reductions in energy requirements. These designs depart considerably from traditional approaches and so this is another challenge that warrants an X-plane research program.

Given that aviation is growing so fast, CO_2 reduction requires reducing the energy needed for flight or reducing the carbon associated with that energy, or preferably both. More than 98% of aviation's CO_2 comes from larger airliners (70 passengers and above) flying distances more than 500 miles. So, to achieve a significant CO_2 reduction, new technology is needed for large airliners, not general aviation or small regional aircraft. Aviation cannot follow the auto industry. It cannot move to electric airplanes. Sufficient technical work has been done so we now understand that there is no battery technology known or on the horizon that can power large electric airliners.

Furthermore, even if there were a scientific breakthrough that enabled a battery powered airliner, that airliner would produce more net CO_2 than do current jet engine powered airliners. This is simply because current airline engines produce considerably less CO_2 per unit power than does the nation's power grid and are projected to do so for several decades. Hybrid-electric approaches at airliner scale now look to save only a few percent in fuel consumption, even given the assumption of greatly improved batteries and electrical gear. So, they are not a solution. NASA's work on the energy reduction side of the problem should focus on more efficient airplanes and engines.

I think it is clear that the only path forward that has the potential to significantly impact aviation's net CO_2 by 2050 is improved airplanes and engines fueled with a liquid hydrocarbon fuel that does not release fossil CO_2 into the atmosphere. Several of these fuels exist today, have been proven safe, and are in limited commercial service. Known as Sustainable Alternative Jet Fuels (SAJF), they can save 80% or more on CO_2, yet are compatible with existing aircraft and fuel infrastructure, while not adversely affecting food and water supplies. Much more can be done to expand their availability, especially to improve their economics. This research area is now the purview of the Departments of Energy and of Agriculture. NASA can play a role in advancing engine technology to reduce emission including CO_2 and exploiting the properties of these fuels.

To close, civil aeronautics is a major economic and trade strength of the United States. NASA contributions have played an important in the past and a strong NASA Aeronautics is need to maintain our strength. The support and leadership that NASA provides is important at all levels – supporting university research and students, stimulating and new concepts and cultivating new technologies, and performing large scale technology validation experiments and demonstrations.

Thank you.

Dr. Alan H. Epstein is the R.C. Maclaurin Professor of Aeronautics and Astronautics Emeritus and former Director of the Gas Turbine Laboratory at the Massachusetts Institute of Technology (MIT). While at MIT, he consulted widely for aerospace, energy, and high-tech industries. He continues to work as a consultant. In 2018, he retired as Vice President Technology and Environment at Pratt & Whitney where he was responsible for setting the direction for and coordinating technology across Pratt & Whitney. He also provided strategic leadership in reducing the environmental impact of P&W's world-wide products and services.

Dr. Epstein has over 140 publications in the fields of aircraft and gas turbine technology, aviation and the environment, rocket propulsion, and microsystems. He was a co-author of the IPCC report on climate change that won the Nobel peace prize in 2007. He has given over 250 plenary, keynote, and invited lectures around the world on topics including aviation and the environment, aerospace propulsion, power and energy, micro and nano systems, and the role of new technology in military affairs. He has over two dozen patents granted or pending on gas turbine and on microsystems technologies.

Dr. Epstein has served on many panels and committees advising the US government, industry, and academia. He is currently the chair of the National Academies of Sciences Aeronautics and Space Engineering Board (ASEB) and member of the NASA Advisory Council. He has also served as chair of the US Board on Army Science and Technology. He has won many international awards for his work in propulsion including seven best paper awards, the American Institute of Mechanical Engineers (ASME) Gas Turbine Award, the ASME Gas Turbine Scholar Award, the ASME R. Tom Sawyer Award, the American Institute of Aeronautics and Astronautics (AIAA) Dryden Lectureship in Research, the International Gas Turbine Institute Gas Turbine Technology Award, the Canadian Aeronautics and Space Institute Turnbull Lectureship, the Engineer's Council Honorary Engineer of the Year Award, and the General James H. Doolittle Award. Dr. Epstein is a member of the U.S. National Academy of Engineering and past chair of its Aerospace Section. He is an Honorary Fellow of the AIAA, a fellow of the ASME and a fellow of the UK Royal Aeronautical Society. He received B.S., M.S., and PhD degrees from MIT.

Chairwoman HORN. Thank you, Dr. Epstein. Dr. Kroo?

TESTIMONY OF DR. ILAN KROO, PROFESSOR OF AERONAUTICS AND ASTRONAUTICS, STANFORD UNIVERSITY

Dr. KROO. Madam Chair, Ranking Member Babin, and Members of the Committee, thank you for the opportunity to speak today. My remarks will deal with NASA's continuing contributions to aeronautics research and development. They represent my personal views, not those of any organization, although they were informed by many years of working with startup companies, government agencies, and university students. All of these groups, and indeed the general public, are aware of the many technology advances that promise to transform aviation not just in the distant future, but in the next decade, and perhaps in the next few years.

So, when I was asked to talk today I looked on my desk, and found that there were all these magazines that discussed just that. And, in fact, headlines from multiple national and international magazines dated this month, and, as the Chair has pointed out, even some dated this week, talk exactly about those things, and they talk—they tout the technologies, and imminent advantage—advances in aeronautics that may result from new technology development. These technologies include many in NASA's research profile. Autonomy, as Dr. Shin mentioned, and includes machine learning, improved flight sensors and actuators. New control theory allows increasingly capable and reliable autonomous systems for aircraft, and it will reduce the cost of commercial air transport, enable on demand aerial delivery of various goods, and increase the safety of both piloted and unpiloted aircraft. Another technology that's talked about in these magazines is new fuels, and efficient high-power electric systems. These will make possible a new generation of environmentally sustainable propulsion, and more efficient aircraft.

So these technology elements are being combined with advanced methods for aero and structural modeling and design to create entirely new types of vehicles from, as you've heard, small subsonic aircraft, with dramatically reduced noise and emissions, to atmospheric satellites that fly without pilots at altitudes above passenger aircraft. This is why an unprecedented number of students are enrolling in aerospace courses and clubs. Why computer science, despite the fact that Stanford, unlike MIT, is a liberal arts school, and they study philosophy, and economics, and things like that, but—the biggest department that graduates the most students is computer science. Still, many of our students are interns at companies that did not exist just a few years ago, and are studying a wide range of these things that will be of use to them in the future. It is certainly one of the most interesting periods in the development of civil aviation.

But many students, and most aviation-related startups, and even many aeronautical researchers, have little idea of what NASA is doing in these technology areas, which is interesting. Articles in the popular press deal with flying cars, and electric airplanes, on demand delivery, and new companies working on supersonic prototypes. But in many of these articles, NASA goes unmentioned. So we have some of these magazines talking about 10 different technologies that are currently under development. Some of them tout how we're going to be delivering blood to Rwanda to help citizens there, and there are these compelling images of small aircraft without pilots delivering things where they are needed. But those small airplanes don't have NASA logos on them. Why is that? It's—it is the case also that many of these companies have to deliver convincing demonstrations to some of the—their investors before NASA has a chance to do the research that's required to make them go to the next level.

[The prepared statement of Dr. Kroo follows:]

Testimony before the Committee on Science, Space, and Technology
U.S. House of Representatives

Hearing on NASA's Aeronautics Mission: Enabling the Transformation of Aviation
June 26, 2019

Statement of
Dr. Ilan Kroo
Thomas V. Jones Professor of Aeronautics and Astronautics
Stanford University

Madam Chair, Ranking Member Babin, and Members of the Committee, thank you for the opportunity to testify today. The following remarks deal with NASA's continuing contributions to aeronautics research and development; they represent my personal views, not those of any organization, although they are informed by many years of working with start-up companies, government agencies, and university students. All of these groups, and indeed, the general public, are aware of the many technology advances that promise to transform aviation – not just in the distant future, but in the next decade, and perhaps in the next few years.

Headlines from multiple national and international magazines, dated this month and this week, tout these technologies and the imminent advances in aeronautics that may result. The technologies include many in NASA's research portfolio: autonomy (including machine learning, accurate flight sensors and actuators, control theory), high-power efficient electric propulsion, new fuels and batteries, and advanced methods for aero-structural prediction and optimization. Increasingly capable and reliable autonomous systems, will reduce the cost of commercial air transport, enable on-demand aerial delivery of various goods, and increase the safety of both piloted and unpiloted aircraft. New fuels and high-power electric systems enable a new generation of environmentally-sustainable propulsion, while advances in aerodynamic and structural design permit entirely new types of aircraft from small supersonic aircraft with dramatically reduced noise and emissions, to atmospheric satellites that fly without pilots at altitudes above passenger aircraft. This is why an unprecedented number of students are enrolling in aerospace courses and clubs, why computer science is the largest degree program at Stanford, and why many of our students are interns at companies that did not exist just a few years ago. It is certainly one of the most interesting periods in the development of civil aviation.

But many students, most aviation-related start-ups, and even many aeronautical researchers, have little idea of what NASA is doing in these technology areas. Articles in the popular press deal with flying cars, electric airplanes, on-demand delivery, and new companies working on supersonic prototypes. But in many of these articles, NASA goes unmentioned. Compelling images of autonomous aircraft delivering blood to clinics in Rwanda do not feature NASA logos, and technical papers from NASA researchers often appear long after companies have needed to provide a demonstration to investors. The large number of future flight concepts and new companies makes it difficult for NASA to function as it has for many years, with a few large, well-known aerospace companies as partners. Without a return to larger NASA aeronautics budgets, NASA may need to focus on a reduced set of intriguing future aircraft.

NASA Aeronautics has taken several steps to encourage partnerships with emerging companies that may have good ideas but need help implementing an analysis or optimizing a design. However, a limited number of Strategic Thrusts and Grand Challenges along with NAE reports and discussions among groups such as the Aeronautics Research and Technology Round Table, may not be sufficiently accessible to the increasingly diverse set of companies, researchers, and technologies of interest. An alternate approach, that has worked well for some space exploration projects, involves a broader range of researchers and organizations in the planning process. Decadal studies have been undertaken by NASA Aeronautics in the past and may provide a means of accommodating a larger number of companies and research topics.

Whatever the structure, NASA must continue to identify and develop critical technologies, create aircraft concepts that can improve people's lives without damaging the environment, support students, companies, and advanced research, all within a budget that is dwarfed by that of a few well-funded start-ups. That they have been able to make such contributions despite these constraints is a testament to the creative engineers and administrators who keep NASA Aeronautics making a difference to the future of flight.

Dr. Ilan Kroo is the Thomas V. Jones Professor of Aeronautics and Astronautics and Director of the Aircraft Aerodynamics and Design Group at Stanford University. From 2010 to 2015 he was the founding CEO of Zee.Aero (now KittyHawk), a company developing electric VTOL aircraft, returning to Stanford in his current position. Professor Kroo consulted for several companies and government agencies including Aerion Corporation and Desktop Aeronautics. Between 1982 and 1985 he served as a Research Scientist in the Advanced Aerodynamic Concepts Branch at NASA's Ames Research Center. Dr. Kroo has over 150 publications in the fields of aircraft design, multidisciplinary optimization, and aviation and the environment, including 9 granted patents on supersonic aircraft concepts and personal air vehicles.

Dr. Kroo has served on many panels and committees advising the U.S. government, industry, and academia. He is currently a member of the National Academies of Sciences Aeronautics and Space Engineering Board (ASEB) and the AIAA Aircraft Design Technical Committee. He has won many awards for his work in aircraft design including the American Institute of Aeronautics and Astronautics (AIAA) Lawrence Sperry Award, the Dryden Lectureship in Research, and the Multidisciplinary Optimization Award. Dr. Kroo is a member of the U.S. National Academy of Engineering and Fellow of the AIAA. He received B.S., M.S., and Ph.D. degrees from Stanford University.

Chairwoman HORN. Thank you, Dr. Kroo. We look forward to hearing more from you when we begin the questions——

Dr. KROO. Very good.

Chairwoman HORN [continuing]. So thank you very much. Dr. Lewis?

TESTIMONY OF DR. MARK LEWIS, DIRECTOR, IDA SCIENCE AND TECHNOLOGY POLICY INSTITUTE, AND PROFESSOR EMERITUS OF AEROSPACE ENGINEERING, UNIVERSITY OF MARYLAND

Dr. LEWIS. Madam Chair, Ranking Member Babin, distinguished Members of the Committee, thank you for the opportunity to testify today. I'm going to focus my remarks on NASA's role in hypersonics research, a field that holds the potential—what I think are truly transformative accomplishments in aeronautics. As I'm sure you all know, hypersonics is a broad area of inquiry. It generally refers to flight in excess of about 5 times the speed of sound, that's Mach 5. An aircraft traveling at Mach 5 is traveling about a mile per second, so that means that an airplane flying from Dulles Airport to London, Heathrow at hypersonic speeds could get there in less than an hour, so talk about transformative.

We've actually been flying hypersonic vehicles of one sort or another since the late 1940s. This is not a new field, but there are still many fundamental problems left to be solved. One of them is propulsion. Conventional jet engines won't work at hypersonic speeds, and that means you have to use either rockets, or what we call advanced air breathing engines, such as scram jets. Also, at high speeds, friction with the air makes the surface temperatures really hot. That means you stress the limits of materials, and so it calls for advances in high temperature materials. Control of a hypersonic vehicle is also an issue, as is the overall design of a hypersonic configuration that's fully integrated with its engines and airframe, and NASA has significant expertise in each of these areas.

So historically NASA Aeronautics and its precursor, the NACA, that Ranking Member Babin referenced, have made notable contributions to the evolution of hypersonic flight, including our basic understanding of the physics of re-entering spacecraft, traveling, in some cases, at 40 times the speed of sound. That work continues today. NASA engineers study the problems associated with decelerating large spacecraft in the thin atmosphere of Mars. They've developed new high-temperature materials, including the material that's going to shield the SpaceX Dragon capsule. That's material that was invented by a team at the NASA Ames Research Center.

That scramjet engine that I mentioned a moment ago was invented by NACA researchers working what is now the NASA Glenn Research Center. They did that work in the late 1950s, and 46 years later engineers at NASA Langley, working with NASA Dryden, now Armstrong, flew the first operational scramjets on the X-43 experimental vehicle, once at nearly Mach 7, 7 times the speed of sound, and again at Mach 10. NASA also did key computational experimental work in support of the Air Force's own unmanned X-51 flights that flew between 2010, 2013. NASA even provided the chase planes that monitored the X-51 craft, gathered essential flight data.

NASA propulsion engineers and materials experts are playing key roles in several programs, including DARPA (Defense Advanced Research Projects Agency) activities, the U.S./Australia high fire flight program. And I'll point out when engineers at the U.S. Air Force's Hyper Velocity Tunnel Number Nine, that's the Nation's premiere high-speed wind tunnel, needed a new way to measure model temperatures, they turned to their colleagues at NASA Langley to do that. NASA has developed many of the standard hypersonic aerodynamics models that we use. The agency also operates test facilities, including the Langley 8-foot-high temperature tunnel that has gathered data on nearly every significant air breathing hypersonic engine, including those that powered X-43, X-51, and the upcoming DARPA Hawk designs. Tunnel—the 8-foot tunnel is an irreplaceable national asset, and not just the tunnel itself, but the NASA test engineers and technicians who operate it.

Research into hypersonic flight may someday lead to ultra-fast commercial aircraft, may lead to new ways to reach Earth orbit with airplane-like launch vehicles, and these are wholly appropriate, I would argue, for NASA Aeronautics research. But the proverbial elephant in the room is that the likely—is the likely military use of hypersonics, including ultra-fast, nearly unstoppable missiles and reconnaissance craft. In 2016, I chaired a National Academies study that reported that both Russia and China were advancing quickly in the field, and moving to operational deployment. We are in a race, and I believe that NASA must help our national address this threat. I further believe that role is completely consistent with NASA's mission, as codified under the *Space Act*. NASA has the capabilities and hypersonics that no other Federal agency can employ.

Now, NASA's hypersonics investments began to languish, starting in 2012, when a roughly $60 million portfolio was allowed to drop to less than $10 million within about 2 years. More recently, NASA's hypersonics funding levels have been on the rise, just as our national programs are hitting limits of capacity and workforce, though they're still at only about half their levels in pre-2012. NASA's re-investment has included much needed maintenance on the Langley 8-foot tunnel, without which some of our national programs would come to a screeching halt. That's a promising start, but for our Nation to lead the world in hypersonics, I argue we must create a challenging future vision.

The future success of hypersonics ultimately hinges on our ability to integrate computational and experimental capabilities. NASA is the ideal agency to lead such an effort. World-class research requires world-class researchers. We must have access to affordable, flexible, world-class modeling and test capabilities, and to do this we need to sustain and expand NASA's hypersonic test infrastructure, including the possible re-commissioning of the hypersonic test facility at NASA's Ohio Plumbrook campus. And, of course, we cannot relinquish our investments in fundamental research, both inside NASA and in the university community that NASA sponsors. With the promise of flying higher and faster, hypersonics is a great way to attract the best and the brightest to careers in aerospace.

In conclusion, I'm convinced that NASA Aeronautics has a critical role to play in pursuing hypersonics research that will transform our civil commercial, and national security activities, and inspire the next generation. In its mission to transform aviation, I know of no worthier investment in the NASA Aeronautics portfolio. Thank you very much.

[The prepared statement of Dr. Lewis follows:]

Testimony before the Committee on Science, Space, and Technology
U.S. House of Representatives

Hearing on NASA's Aeronautics Mission: Enabling the Transformation of Aviation
Dr. Mark J. Lewis, IDA Science and Technology Policy Institute
June 26, 2019

Madam Chair, Ranking Member Babin, and distinguished Members of the Committee, thank you for the opportunity to testify today. I will focus my remarks on NASA's role in hypersonics research, a field that holds the potential for truly transformative accomplishments in aeronautics.

As I am sure you know, hypersonics is a broad area of inquiry that generally refers to flight in excess of Mach five, or five times the speed of sound – about a mile per second. An airplane flying at hypersonic speeds could travel from Dulles Airport to London Heathrow in less than an hour. Talk about transformative!

We have been flying hypersonic vehicles of one sort or another since the late 1940's, but there are still many fundamental problems left to be solved, especially for vehicles that remain in our atmosphere instead of passing through it on the way to space or back. Propulsion is one – conventional jet engines will not work at hypersonic speeds, and so rockets or "airbreathing" engines such as *scramjets* must be used. At high speeds, friction with the air makes surface temperatures high, stressing the limits of materials. Control of a hypersonic vehicle is also an issue, as is the overall design of an optimized, fully-integrated configuration. NASA has significant expertise in each of these areas.

Historically, NASA aeronautics and even its precursor, the NACA, have made notable contributions to the evolution of hypersonic flight, including our understanding of the physics of reentering spacecraft, traveling in some cases more than 40 times the speed of sound. That work continues today as NASA engineers study the problems associated with decelerating large spacecraft in the thin atmosphere of Mars, and develop new high temperature materials, including the material that will shield SpaceX's Dragon capsule, invented by a team at NASA Ames.

That scramjet engine that I mentioned was invented by NACA researchers working at what is now the NASA Glenn Research Center in the late 1950's. Forty-six years after their work, engineers at NASA Langley and NASA Dryden (now Armstrong) flew the first operational scramjets on the X-43 unmanned aircraft, once at nearly Mach 7, and again at Mach 10. NASA also did key computational and experimental work in support of the Air Force's unmanned X-51 flights between 2010 and 2013. NASA even provided the chase planes that monitored the X-51 craft and gathered essential flight data.

NASA propulsion engineers and materials experts are today playing key roles in several DARPA hypersonic programs, as well as the joint U.S.-Australia HIFiRE flight program. And when engineers at the U.S. Air Force's Hypervelocity Tunnel Number 9 – the nation's premiere high-speed wind tunnel located in nearby White Oak Maryland – recently needed a new way to measure model temperatures, they turned to their colleagues at NASA Langley.

NASA has developed many of our standard hypersonic aerodynamics models. The agency also operates hypersonic test facilities, including the Langley 8-Foot High Temperature Tunnel, that has gathered data on nearly every significant airbreathing hypersonic engine, including those that powered X-43, X-51, and the upcoming DARPA HAWC designs. The 8-Foot is an irreplaceable national asset – not just the tunnel itself, but the resident knowledge of the NASA test engineers and technicians.

Research in hypersonic flight may someday lead to ultra-fast commercial craft, and maybe even new ways to reach earth orbit with airplane-like launch vehicles; these are wholly appropriate areas for NASA aeronautics research. The proverbial elephant in the room is the likely military use of hypersonics, including ultra-fast, nearly-unstoppable missiles and reconnaissance craft. In 2016 I chaired a National Academies panel that reported that both Russia and China were advancing quickly in the field, and moving to operational deployment. We are in a race, and I believe that NASA *must* help our nation address this threat. I further believe that role is completely consistent with NASA's mission as codified under the Space Act. With knowledge of all aspects of hypersonic flight, from basic physics to test and design, as well as ties to the broader research community, NASA has capabilities in hypersonics that no other federal agency can deploy.

NASA's hypersonics investments began to languish starting in 2012, when a roughly $60M portfolio was allowed to drop to less than $10M within two years. More recently NASA's hypersonics funding levels have been on the rise, just as our national programs are hitting limits of capacity and workforce, though they are still at only about half their 2012 levels. NASA's reinvestment has included much-needed maintenance on the Langley 8-foot Tunnel, without which some of our national programs would come to a screeching halt.

That's a promising start, but for our nation to lead the world in hypersonics, we must first create a challenging future vision. The future success of hypersonics ultimately hinges on our ability to integrate computational and experimental capabilities, and NASA is the ideal agency to lead such an effort. World-class research requires world-class research*ers* who must have access to affordable, flexible world-class modeling and test capabilities. To do this we need to sustain and expand NASA's hypersonic test infrastructure, including the possible recommissioning of the Hypersonic Test Facility at NASA's Ohio Plum Brook campus. And of course, we cannot relinquish our investments in fundamental research, both inside NASA and in the university community that NASA sponsors. With the promise of flying higher and faster, hypersonics is a great way to attract the best and brightest to careers in aerospace.

In conclusion, I am convinced that NASA Aeronautics has a critical role to play in pursuing hypersonics research that will transform our civil, commercial, and national security activities and inspire the next generation. In its mission to transform aviation, I know of no worthier investment in the NASA Aeronautics portfolio.

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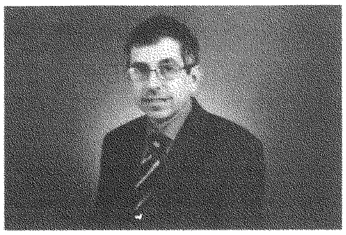
Director, IDA Science and Technology Policy Institute



Dr. Mark J. Lewis is the Director of the IDA Science and Technology Policy Institute (STPI), a federally funded research and development center. He leads more than 40 researchers providing analysis of national and international science and technology issues for the Office of Science and Technology Policy in the White House, the National Science Foundation, and the National Institutes of Health, among others.

Prior to taking charge of STPI, Dr. Lewis served as the Willis Young, Jr. Professor and Chair of the Department of Aerospace Engineering at the University of Maryland. A faculty member at Maryland for 24 years, Dr. Lewis taught and conducted basic and applied research. From 2004 to 2008, he was the Chief Scientist of the U.S. Air Force. From 2010 to 2011, he was President of the American Institute of Aeronautics and Astronautics (AIAA). Dr. Lewis also served as a member of the Air Staff and principal scientific adviser to the Chief of Staff and Secretary of the Air Force. He provided assessments on a wide range of scientific and technical issues affecting the Air Force mission.

Dr. Lewis attended the Massachusetts Institute of Technology, where he received a Bachelor of Science degree in aeronautics and astronautics, Bachelor of Science degree in earth and planetary science (1984), and both a Master of Science degree (1985) and a Doctor of Science degree (1988) in aeronautics and astronautics.

Dr. Lewis is the author of more than 300 technical publications and has been an adviser to more than 60 graduate students. He has also served on various advisory boards for NASA, the Defense Department, and the Air Force, including two terms on the Air Force Scientific Advisory Board.

Dr. Lewis is a Fellow of the Royal Aeronautical Society, a Fellow of the American Society of Mechanical Engineers, and an Honorary Fellow of the AIAA. His awards include the DOD Exemplary Civilian Service Award, Meritorious Civilian Service Award, Exceptional Civilian Service Award, the IECEC/AIAA Lifetime Achievement Award, and the Air Force Association's Theodore Von Karman Award. He was also recognized as an AIAA National Capital Young Scientist/Engineer of the Year (1994) and an Aviation Week Laureate (2007).

About IDA

IDA is a non-profit corporation operating in the public interest. Its three federally funded research and development centers provide objective analyses of national security issues and related national challenges, particularly those requiring extraordinary scientific and technical expertise.

Chairwoman HORN. Thank you very much, Dr. Lewis, and we'll observe any future back and forth between the Stanford and the MIT crowd out there. We'll keep an eye on you. At this point we'll begin our first round of questions, and the Chair recognizes herself for 5 minutes.

Doctors Epstein, Kroo, and Lewis, this Committee will be working to reauthorize NASA this year, and I've got a number of questions. Just briefly, what are your top three priorities for aeronautics for NASA authorization, and why? We can just go down the——

Dr. EPSTEIN. OK. Well, my personal passion is for anti-noise. More accurately, NASA research to dramatically reduce the noise impact on our communities. I think that same sort of research also helps make much more efficient airplanes. So high on the priority would be a—enough funding to start an X airplane for subsonic commercial travel, with enormously reduced noise, and much reduced CO_2.

The second would be everything associated with UAM, which is an enormous potential market, a transformer of society, and I think we're at the most risk internationally of—we don't have a lead yet. We'll see if we end up with one. Thank you.

Dr. KROO. So I believe that many of these new companies, as well as the old companies, very much need help from NASA, and one has to figure out how it is that NASA can work with the many new players, the many new participants, in this field who are going to make some of these things happen, and I think that that is not clear yet how that will be done, but it's important to make sure it happens.

Dr. LEWIS. Well, of course I'm going to say hypersonics.

Chairwoman HORN. I would never have guessed.

Dr. LEWIS. That's shocking. And not just facilities, but also workforce and fundamental research. Number two, I would say the X plane program, and the X-59 is a particularly exciting example. We need to fly things, we need to get experience in flight, and we need to be pushing the flight envelope. And then three, I'd say fundamental research, and I would take my hat off to the NASA Aeronautics Research mission director. I think they've led the way at NASA in fundamental research in support of universities and students, and feeding into our workforce.

Chairwoman HORN. Thank you. And, as I noted in my opening statement, the CTOs—the Chief Technology Officers—of those seven companies came together at the air show to talk about how the aeronautics industry can work to reduce emissions and—in a sustainable way for aviation, which is important for us to address both. And the joint statement, which I submitted for the record has a three-prong strategy. One, improving aircraft and engine design and technology to improve fuel efficiency and reduce CO_2 emissions; two, supporting sustainable alternate aviation fuels; and three, developing a new aircraft propulsion technology to enable a third generation of aviation.

Dr. Epstein, given your experience in this industry, how important is a clear strategy for the industry's ability to plan for future technology and workforce needs? I think you touched on it a moment ago, but if you want to expand?

Dr. EPSTEIN. The industry reminds me of the comment by Benjamin Franklin, we hang together, or we hang separately, and the attack around the world on aviation affects all of us. In terms of climate change impacts on CO_2, the sustainable alternative jet fuel is enormously important, and how that affects the agricultural economy in this country I think is equally important. And so, for example, ethanol is a big factor in much of the country. The auto industry doesn't want it. Aviation would embrace it. So getting not just the purview of this Committee on Science and Technology, but Energy and Agriculture as well to focus on a lot of this is, I think economically important.

Chairwoman HORN. And for the rest of the panel, I would love to hear which of the three prongs of this strategy you think NASA can get the most bang for the buck, as it were, to move forward for investment on the NASA side.

Dr. KROO. Well, I must say I agree with many of these comments, and they will get a lot of mileage out of these investments. I do think that, in the near term, things such as alternative fuels, and increased efficiency, are much more important than the longer-term advances, and many of these longer-term concepts require very new ideas in both fuels and propulsion systems.

Chairwoman HORN. Dr. Lewis?

Dr. LEWIS. And I would agree as well. I argue that an aerospace system is fundamentally an energy conversion system. As aerospace engineers, we do everything we can to get every last bit of energy out of our available fuel—out of our available energy supply. So aerospace has a lot of lessons to propagate to other parts of engineering disciplines on how to be energy efficient, how to use fuels effectively, how do to alternate fuels, how to do alternate energy sources, and I think NASA has a very important role to play in that.

Chairwoman HORN. Thank you. Dr. Shin, would you care to comment briefly?

Dr. SHIN. Yes. I think, as the other witnesses summarized, and—in terms of priorities in near-term, and mid-term, and longer-term contributions, we—I want to say that NASA has been working on all those areas, improving the fuel efficiency and reducing emission from the engine research. And also we have done a major flight test of the alternative fuels with, actually, international partners from Germany, and Canada, and Japan. So—and then we're also working on lighter, stronger structures, so reducing the weight of aircraft will require less fuel burns. So, all those things need to be coming together. And, as other witnesses say, that it's not one magic bullet, or it's not one big gun that we can use to reduce these fuel burns.

And, in fact, if I may add, in fact, I was at Paris Air Show last week, and I actually met with these industry CTOs. After the news conference they had, they meet regularly, and I was invited to join that meeting, so we did amply talk about this, and they were very appreciative of what NASA has been doing.

Chairwoman HORN. Thank you, Dr. Shin. I've exceeded my time. Dr. Babin?

Mr. BABIN. No problem. Thank you, Madam Chair. Dr. Lewis—let's see, where was that article. OK, yes. A recent New York Times article, which I would like to ask to be put into the record, if you don't mind, if there's no objection——

Chairwoman HORN. No objection.

Mr. BABIN [continuing]. Highlighted the current state of hypersonic research in the world, and it laid out the threat posed by hypersonic weapons being developed by China and Russia. General John Hyten, Commander of the U.S. Strategic Command, told the Senate Armed Services Committee in March 2018, "We don't have any defense that could deny the employment of such a weapon against us." Your testimony lays out how NASA's infrastructure and expertise enable our Nation's overall hypersonic program. Is greater coordination between NASA and other government agencies necessary to ensure American leadership and national security?

Dr. LEWIS. Thank you, Congressman. Well, first, I would say that NASA is doing a very fine job of coordinating with Department of Defense (DOD), and they've become a critical player in some of the work that's underway. I will give you an example. In my testimony I mentioned the 8-foot tunnel at NASA Langley.

Mr. BABIN. Right.

Dr. LEWIS. That's one of only two locations in the United States where you can do a full-scale hypersonic engine test. Right now the other location is not available, it's down for maintenance. So NASA is absolutely critical for much of the work that we're doing. But I think it goes beyond that. If you—I mentioned some of the contributions of NASA engineers, everything from material science, to controls, to understanding of propulsion technologies. NASA has been, and continues to be, critical players in each of those aspects, and supporting the national efforts, including Air Force—efforts with the Air Force, efforts with DARPA, and even some fundamental research efforts that were funded by the Department of Defense. So yes, I think they're absolutely critical.

Mr. BABIN. OK. Thank you, Dr. Lewis. The next question is for Dr. Shin and Dr. Lewis. NASA conducts aeronautics research on urban air mobility, and is developing the X-57 Maxwell, an electric aircraft that will demonstrate technologies to reduce fuel, noise, and emissions. I presume there are market demands for such technologies from either commercial aviation, general aviation, or both. From the dawn of aviation we've seen that top down, centrally planned research and development approaches are often eclipsed by free market responses to technological challenges. In face of other nations significantly subsidizing their aeronautics and aviation sectors, how should NASA approach this challenge of supporting free market principles, while also maintaining long-term aeronautics leadership? Dr. Shin, if you would first?

Dr. SHIN. Yes. Thanks for the question. In terms of urban air mobility, just like your emphasis on the free market economy that our Nation holds, we believe in that, so we are not—as an example, NASA, as a government entity, we are not investing to duplicate vehicle designs in this new industry because there are, last time I checked, over 150 entities working on these various design concepts, and billions of dollars are being invested from private sectors. So what we are working on is how do we enable these private investment to become the real, viable, and scalable market by working on system-level issues, community-wide issues, such as noise reduction and safety—ensuring safety, and how do we actually expedite, and cost-effective certification can be allowed for these vehicle designers. So, working with FAA, I think we have found a really nice government role, again, closely working with industry, but that's the way we believe how we enable this exciting future.

Mr. BABIN. OK. All right. Thank you. And, Dr. Lewis?

Dr. LEWIS. So I would argue that NASA's primary role is investing in areas that industry won't, or doesn't have the wherewithal, or that it's too far term. And I—again I would congratulate the NASA portfolio, because I think they've done a fine job of identifying key investments, key areas. If you look at some of the work that NASA's done, for example, on our advanced configurations for commercial airliners, they've done things that, frankly, I can't see an industry partner doing right now because it's really too speculative. In propulsion, the work that NASA has done looking at very advanced propulsion, again, wholly appropriate, because I don't see it as something that the industry necessarily would have the resources or the wherewithal to invest until NASA has proven the concept, and then handed it off to industry. I think we've got many examples of technologies that NASA has helped develop, and, once they developed it, were able to hand off to industry very successfully.

Mr. BABIN. OK. Thank you very much. And I've got more questions, but I'm out of time, so I'll yield back.

Chairwoman HORN. Thank you, Mr. Babin. The Chair recognizes Mr. Olson for 5 minutes of questions.

Mr. OLSON. I thank the Chair, and welcome to our four expert witnesses. I'll open with an observation. Much has been said about Stanford and Harvard. Those are great, great schools to be sure, but, as a graduate of Rice University in Houston, Texas, we call those schools the Rice of the West Coast and the Rice of the East Coast, and that's just the way it is.

My first question for you, Dr. Shin and Dr. Lewis, as a former Naval aviator, I have a great interest in the low boom flight demonstration projects. As was mentioned by I think Dr. Epstein, we have not allowed supersonic flights over America since 1973. My district is home to Ellington Joint Reserve Base. As you all may know, last year NASA test pilots flew modified F-18s out of Ellington to do some series of tests of low noise level sonic booms. It was called QSF-18. If possible, can you all update me on this project, especially if these test flights can help with supersonic travel in the future? Dr. Shin?

Dr. SHIN. Yes. I want to say up front, many things to that community, and also we tested that low boom through the customized maneuver because we don't have a low boom supersonic airplane as yet. We're building it, in collaboration with Lockheed Martin. But in the city of Galveston, we actually flew that F-18 that you mentioned, and—with tremendous support from Ellington and Johnson Space Center. And the community response has been actually very positive, that they actually liked being—participating in that flight test, measuring the community response.

So the best measure of success, in my view, is the city of Galveston asked us, NASA people, to please come back when you actually have X-59 completed, and do this again in our community, because this is exciting. And this is exciting because we are trying to help flying public, general flying public, not the rich people only, but flying public to enjoy the supersonic flight, commercial supersonic——

Mr. OLSON. I'll pass those comments on to Mr. Weber, because Galveston is in his district. As you mentioned, too, they were so excited because, for the first time ever, the Johnson Space Center participated in operations in the Earth's atmosphere, not in the vacuum of space. Dr. Lewis?

Dr. LEWIS. So I share, I think, a frustration that you alluded to, that we are not flying at supersonic speeds today. It's been over 15 years since we had commercial supersonic travel in the U.S. And, of course, you know, in the 1960s the U.S. had its own plan to build a supersonic transport, NASA had a subsequent program in the 1990s, and yet we're still flying at about the same speed we flew in the 1950s, so I would love to see supersonic travel.

Last month I and some of my colleagues were—had the privilege of visiting NASA Armstrong, and to climb on—look at the work that's being done on the X-59, and I have to tell you, it's absolutely phenomenal progress. It's a program that's basically getting NASA back into the flight test business. We got to fly the simulator, I got to crash the simulator, and it's—I think it's going to be an important milestone not in helping us re-introduce supersonic flight, but also getting NASA back into the flight test rhythm that is so critical to our industry.

Mr. OLSON. Thank you. Final question for Dr. Shin. In your testimony you mentioned that there'll be excessive growth in aviation in the future, and a shortage of pilots to fly these future aircraft. As you probably know, Ellington Field has been selected as a commercial spaceport. It's been approved. Their plan is for space tourism, basically following the same profile that Alan Shepherd followed on the first Mercury launch. Take off horizontally, go vertical, go into space for maybe 10, 15 minutes and come back and land. They're going to need pilots. Our current aviation needs pilots. So how can NASA help recruit, develop, and train our future pilots, especially ones that are going into space?

Dr. SHIN. Yes. Whether we stay in the air or go into space, as you mentioned, the pilot shortage could become a real issue, so we've been working with our industry to bring more autonomy in the cockpit. I'm not suggesting that we are going to reduce the number of pilots in the cockpit, but by introducing safe, and efficient, and cost-effective autonomous systems, on top of what we already have, could probably reduce the workload of the pilots, and pilots' roles could be changing in the future. So some of these measures need to be introduced with care, of course, but some of these measures need to be researched for the longer term. It's not a—solution, or it's not something that we're going to just do it in a hurry. So that's what—we are working with industry.

Mr. OLSON. I yield back. Thank you very much.

Chairwoman HORN. Thank you. The Chair now recognizes Mr. Posey for 5 minutes.

Mr. POSEY. Thank you, Madam Chair, for holding this Committee, and thank the witnesses, very impressive, for attending today and sharing your knowledge with us. In keeping with today's subject, NASA's aeronautics mission, enabling the transformation of aviation, it was interesting to hear Dr. Lewis say he thinks NASA's mission is essentially doing those things that private industry cannot do, which I pretty much think is the role of government, you do for the people what the people cannot do individually, you do collectively for them.

And, Dr. Shin, I heard your reference to working with FAA, and having some good experiences, but it brings to mind some very bad experiences that I've seen with FAA, a terrible waste of resources. You may recall—you're all old enough to recall when the United States basically controlled 100 percent of the world's commercial launch market for satellites, commercial satellites, and, through overregulation of Federal bureaucrats, we parlayed that into about 15 percent, almost completely choked the golden goose, and created the competition that we have today for the commercial launches in other countries.

You mentioned space support vehicles earlier. We have a contractor in my district, Space Support Vehicle. They've done years and years' worth of parabolic missions for NASA. It's so much easier to put an experimental of an F-104 with a pilot that's flown a zillion hours, and test the gravitational effect of the payload than it is to launch a dispensable rocket, or whatever. And, you know, that's one little company. They decided, you know, we'd like to take people up too for this, there's an interest in doing that, so they applied to license to the FAA. And the FAA said, well, you know, you're not a jet to go from Washington, D.C. to Orlando 50 times a day, and you're not Virgin Galactic, that we licensed before they ever put the first vehicle in the air, so we're not going to give you a license. I mean, they could get this license in any other country in the world, be delighted to have that business, but the unelected, unaccountable bureaucrats at the FAA couldn't get off center.

So during the last session then Majority Leader McCarthy, with the support of a lot of co-sponsors passed legislation and said, you will be creating a licensing category for the space support vehicles, whereupon they have kind of refused to do that. And I'm wondering if you have other areas where you have observed this same kind of counterproductive behavior. I'd like to hear about it. Anyone.

Dr. SHIN. I'm sorry that you have had a lot of those examples, but from where I sit, I think, in the aviation side, FAA leadership, and our management and technical people, have really stepped up in trying to be proactive in opening up these—a lot of exciting markets that——

Mr. POSEY. OK, so you haven't experienced the downside. Anybody else experienced the downside, or am I supposed to take this personal? I'll take it personal, and work on their budget accordingly.

Dr. Shin and Dr. Lewis, other agencies fund hypersonics at much higher levels than we do, however, NASA has unique facilities and expertise in that field, you know? Is there an opportunity for NASA to conduct work on a reimbursable basis for other agencies?

Dr. SHIN. I think that is entirely possible. And, as Dr. Lewis mentioned in his testimony, we have been cultivating a really robust, and very symbiotic mutually beneficial relationship with DOD in particular. But I think we can certainly increase the partnerships with other government agencies, and—because we have that core capability—technical capability both in workforce and in the facility as well.

Mr. POSEY. OK, Dr. Lewis?

Dr. LEWIS. So, as I mentioned, NASA's budget in hypersonics is a tiny fraction, frankly, of what the DOD is spending. But what they bring to the table is incredibly impressive. They've got depth of knowledge, they've got expertise. They understand aspects of the fundamentals that no other part of the government, which I'm aware, has. And I can cite success story after success story where NASA worked with the DOD in the hypersonic realm.

One I'll give you right off the top of my head was when the Air Force was doing the X-51 program. So, we tested the engine for X-51 in the NASA facility. Then we had NASA engineers working on the X-51 program. We had NASA engineers in the control room the day of the first flight of X-51. I'm here to tell you if we didn't have those—that support, I don't think the program would have been as successful. It's absolutely critical.

Mr. POSEY. That's awesome. Madam Chair, I yield back. Thank you.

Chairwoman HORN. Thank you, Mr. Posey.

The Chair now recognizes Mr. Foster for 5 minutes.

Mr. FOSTER. Thank you, Madam Chair, and thank you to our witnesses.

Let's see. I've been musing about this low sonic boom technique, and I was wondering if any of you were willing to try to take a stab at telling a physicist how—you know, what are the actual breakthroughs that make it different than my memories as a toddler, listening to the sonic booms from the military jets operating out of Truax Air Field? What is new in the physics or in the design space makes this feasible?

Dr. SHIN. I'll give a stab at it, and—sure the witnesses are far more qualified to answer that.

Certainly, we cannot change the physics or alter the physics, but what we were able to do is breaking the intensity of the shocks. So, rather than having the one big bow shock from the nose or the back end of the aircraft that shows the typical N-shape shockwaves, we break into smaller shocks and then they don't coalesce. They don't coalesce——

Mr. FOSTER. Right, you just phase them so they partially cancel? Is that the basic plan?

Dr. SHIN. That's one technology we developed.

Mr. FOSTER. Yes, sure, Dr. Kroo?

Dr. KROO. I think that is absolutely right. We could do some of that many years ago, and the additional technologies and breakthroughs that have happened have to do with improving computational capabilities for predicting these things before having to take so long to build them.

Mr. FOSTER. And so, this will typically only work at one velocity to get the cancellation between all the wakes?

Dr. KROO. It actually works over a range of speeds, but over a smaller range, you can cancel out more of it.

Dr. EPSTEIN. I'll add something else. One is this was actually a theory developed by NASA, so no, it isn't new physics. It's understanding physics and exploiting your understanding. And because much of the action is in the far field, far away from the airplane, it's inadequate to test it just in a wind tunnel. That's why—we will fly a vehicle like this. Of course, it ends up as a strange looking long, skinny vehicle, but that's what the physics demands. And I certainly expect the X-59 to validate that.

Mr. FOSTER. All right, that's interesting.

Now, for a long time, I've wondered if there was some analog of noise canceling earphones that could be applied to the end of jet engines. I take it most of the takeoff noise is just turbulence in the back end of the engines, if I understand things correctly. What has ever been looked at, and is that still a fertile field to plow?

Dr. EPSTEIN. Airplane noise has been worked on for decades. It used to be rock bands were as loud as airplanes, so don't go to the rock concert. Rock concerts are still just as loud, but the airplanes have gone from about 125 dB down to 85.

Mr. FOSTER. Um-hum.

Dr. EPSTEIN. And on the newest airplanes, the exhaust jet is not the major noise source, the fan is. And so, it doesn't matter whether you turn the fan with an electric motor, it's producing most of the noise. On the latest ones, on approach, if you shut the engines down, you wouldn't hear it on the ground because it's the airframe making most of the noise.

Mr. FOSTER. On approach, but that's not——

Dr. EPSTEIN. Well——

Mr. FOSTER. The complaints come from takeoff. At least around O'Hare, they come from takeoff.

Dr. EPSTEIN. Well actually, I addressed the O'Hare noise group. The complaints come from everywhere, I think.

But strictly speaking, the noise is the fan noise. People have looked at active cancellation. You use some of it now. You do acoustic cutoff in the ducts by design of the physical acoustics. As we move to bigger fans, they're subsonic and it's a whole new world. So, I think there can be enormous progress in noise reduction. Because we've reached a cusp in our understanding.

Mr. FOSTER. Yes. If I can go back to the low boom scenario. What is the range of velocities that you're reasonably hopeful that will work commercially? Are you still in the situation where the fuel consumption per mile is very non-linear as you keep increasing it? And so, what is the range of velocities that you really eventually hope that will operate over, in a commercially viable way?

Dr. KROO. There is a range. Probably the commercial viability is more related to the efficiency of these designs, but certainly in the Mach 1.-something to 2.-small number, these technologies can reduce the boom on the ground.

Mr. FOSTER. OK. Thank you, and it looks like my time is up and I yield back the remainder.

Chairwoman HORN. Thank you very much, Dr. Foster.

I'm going to ask another round of questions. I think the Ranking Member will be back shortly. Since we had to move it around, I think we've lost a number of our Subcommittee Members today.

Dr. Shin, I want to go back to one of the points we started with about workforce development, and the importance of aviation and aeronautics to the Nation and our economy, and what that means also for NASA.

In my opening statement, I raised the question of whether or not we will have the workforce to realize the opportunities that we're working toward. So, along those lines, the NASA Advisory Council's Aeronautics Committee found that the next generation of aviation workers will need a different set of skills than the current generation, including artificial intelligence, cybersecurity—the cutting-edge issues in research that NASA is doing in order to handle the new technology, such as urban air mobility, drones, clearly hypersonics is another area that is important, and the nature of autonomy.

So, how is NASA helping to prepare the workforce of this rapidly approaching future in aviation systems?

Dr. SHIN. Thank you. I think Madam Chair's observation and points are spot on. The aviation—not only aviation, but the entire 21st century industrial sector is changing because of the digital transformation to even new technologies, and the new ways of doing business.

So, aviation industry as a whole, I think, it is experiencing and will experience—continue to experience competition of the top talents with more IT or those industries.

So, what NASA—what we believe is we have to provide exciting missions. We are celebrating 50th anniversary of Moon landing this year, and I am the product of Apollo 13—11 Moon landing. So, we believe that providing that exciting missions so that the younger generation can actually look up to what they can do and what they can accomplish in aviation, be it really the key.

Chairwoman HORN. Thank you, Dr. Shin.

A short question. What, if any, additional hiring authorities might NASA need to attract that workforce?

Dr. SHIN. Our Human Capital Management office has been working really hard to figure out whether we can get more flexibility. So, I'm certainly not an expert in answering the question, but I think our agency, Human Capital Management can provide more details.

Chairwoman HORN. If you want to take that for the record and come back to us, that's great.

So, another question, turning a little bit toward some of the points that Dr. Lewis—that you made, especially around the importance of NASA and government investment in those cutting-edge technologies before they're ready to move onto the commercial sector.

I noted in my opening statement the shift in budget, and looking forward with the important research and development that NASA needs to do in hypersonics, in urban air mobility, in noise, and other things. We are looking toward a likely decrease of funding for Fiscal Years 2023 and 2024.

So, my question for each one of you quickly is how would such decreases of up to 12 percent affect the development of innovative capabilities such as supersonics, hypersonics, urban air mobility, and in aeronautics research, and then the follow on transition to commercialization?

Dr. KROO. In many of these areas, not developing these technologies will mean many of the possible airplanes that companies would develop are just not going to get developed. This is really NASA's role, as Dr. Shin has mentioned, and they're doing a very good job of it to decrease that rather than increasing that at a time when so many new possibilities are on the horizon is probably not the right thing to do.

Dr. EPSTEIN. If I can add to that, it isn't that they may not be developed. They won't be developed in the United States. Actually, I could identify 300 people working on air mobility or stating they've done that, and most of them are not U.S.-based.

And so, it really is a point not of replacing an industry, telling industry what it may do, but enabling industry to make an investment that's reasonably prudent by providing a technology base.

Dr. LEWIS. And if I can build on that, I'll offer a historical example. NASA flew their X-43 for the last time in 2004. There was a 6-year gap between the time NASA flew its vehicle and the Air Force flew X-51, which is essentially a logical follow on to X-43. That 6 years, I believe, was one of the reasons that foreign competitors were able to gain an advance in the hypersonics field.

We did the homework for them, and then they were able to build on that investment and move forward at a pace that was faster than ours.

Chairwoman HORN. Dr. Shin, would you care to add anything?

Dr. SHIN. Yes, I think other witnesses have very graciously offered the supporting comments. But I think what we have been really improving is within the given budget, how most effectively and efficiently we can use that precious funding toward the most compelling and impactful technologies. Then I think by working with industry and other government agencies in very close relationship for the past 10 years or so, we have really maximized return on investment.

Chairwoman HORN. Thank you, Dr. Shin. I'm hearing from all of you it's a matter of U.S. leadership in aeronautics and aviation.

Dr. Babin?

Mr. BABIN. Yes, ma'am. Thank you.

This question is similar to the one that Mr. Olson had asked a while ago, but there is a little twist on it.

Dr. Shin, NASA is developing a low boom demonstrator mission, the X-59, to develop new technologies to lower the noise associated with supersonic flight. NASA recently conducted a series of quiet supersonic research flights off the coast of Texas near Galveston to test ways to measure the community's response to the unique acoustic experience.

And just a few weeks ago, the FAA announced that it is developing regulations to enable the resurgence of supersonic flight. How are these efforts coordinated?

Dr. SHIN. We're very, very much coordinating our efforts between FAA and NASA. As a matter of fact, I actually even met with the acting administrator of FAA yesterday to just talk about this.

So, there are two challenges at the moment. Very quickly, one is certainly trying to influence regulatory agencies around the world so that this ban on supersonic flight over land is changed or lifted. So, that's what NASA X-59 will do. And then there's another challenge that is landing and takeoff noise from supersonic airplanes, should there be any commercial supersonic airplanes.

So, that's what FAA is leading.

Mr. BABIN. Yes.

Dr. SHIN. So, we are collaborating with FAA to provide technical support for them to come out with regulatory standards.

Mr. BABIN. I understand. Thank you.

You know, also this next one, Dr. Shin. NASA's recent budget request proposes reorganizing the management of aeronautics test facilities. This comes on the heels of a similar reorganization several years ago. What was the rationale for this restructuring?

Dr. SHIN. The main rationale is these are national asset-level wind tunnels, and certainly aeronautics—my mission directorate has been the custodian and keeper of those major wind tunnels for the agency and for the customers and participants as well.

But other mission directorates also use these wind tunnels, so it is truly agency-level activity and agency-level issues. So, the agency has moved that to agency-level management, not just from the Aeronautics research mission directorate.

So, that's all there is to it. There's no content reduction. There's no budget reduction, anything.

Mr. BABIN. I understand.

OK. That takes care of me. Thank you. I yield back.

Chairwoman HORN. Thank you very much, Mr. Babin.

The Chair recognizes Mr. Foster for 5 minutes.

Mr. FOSTER. Thank you, Madam Chair.

You know, one of the obviously enabling technologies for electric airplanes is the energy density of batteries. I represent Argonne National Lab, which is the central lab organizing a national collaboration, with the goal of something like 5 times higher energy density than current lithium ion. And if you look at the feasibility in different areas, you know, what sort of energy density improvement do you really need to get, you know, commercial airliners versus, you know, local delivery drones, you know, all the different—which, you know, I guess these applications turn on one at a time as your batteries get more capable. I was wondering what the milestones there we should aim for are?

Dr. EPSTEIN. Well, different answers for different airplanes.

So, the drones are almost good enough now. So, a factor of two in density would help a lot in a commercial sense, especially—so, it's a cost issue as well as that.

Jet fuel burned in a modern engine is 100 times the energy density of the batteries, so should the batteries get 10 times better than the current batteries, the airliner could taxi out to the end of the runway, and then would have to turn around and go back to the terminal because you need a 45-minute reserve before you take off in case you can't land immediately. So, for airliners, it's a long, long way.

The urban air mobility vehicles, however, these are things that only need ranges of 20, 50, 80 miles, they're factor of 5 improvement with the associated economics would be very useful, and also that might allow you to optimize larger airplanes better. But it doesn't let you—electric power——

Mr. FOSTER. You're not going to cross the Pacific——

Dr. EPSTEIN. Not without——

Mr. FOSTER. A factor of 100 is what you said, or 50 at least?

Dr. EPSTEIN. Not without a very long extension cord.

Mr. FOSTER. You know, I have expressed the opinion in this room many times that I think that NASA doesn't spend enough on potentially transformative technologies to get things into low-Earth orbit for cheap. You know, there are a large number of concepts for this, you know, everything from space elevators to electromagnetic launch to laser-assisted launch.

We were able to get to bump up the budget in just the last couple weeks of the NASA Advanced Innovative Concept, NAIC, but it's still tiny. We bumped it up from about 8 to roughly $15 million, if it survives the Senate. And so, some of these concepts have little to do with aeronautics, and some of them do. I was wondering what you think the most promising, you know, to be explored areas there that might really have a shot at dramatically lowering the cost of getting things into low Earth orbit?

Dr. EPSTEIN. Well, to steal Dr. Lewis' thunder, a combined cycle hypersonic propulsion system would let—as the Nation tried to do with the National Aerospace Plane in the 1980s, and that was a bridge too far for our technology at the time. That was national defense. That was probably the best chance of regularizing things.

But in today's Wall Street Journal online, there's an article which shows what's going on in space in terms of activity. And one of its graphs shows that the cost of a pound to orbit was $34,000 on the shuttle. On a Falcon X Heavy, it's $640. So, the cost has come down considerably, and if the new entrants are successful, I expect it to be much less expensive as well.

Mr. FOSTER. Dr. Lewis?

Dr. LEWIS. So, one of the challenges is that a modern rocket engine is really an amazing piece of equipment. It delivers efficiencies—energy efficiencies higher than almost any other machine I can think of on the planet. And so, trying to do better than a rocket engine is really quite a challenge.

Mr. FOSTER. You know, what disturbs me is when you look at these missions to Mars, there's very little on them that would not be completely understandable to Wernher Von Braun.

Dr. LEWIS. Correct.

Mr. FOSTER. You know, you very rapidly went to the asymptote for the performance of chemical rockets, and I really think it's time to step back and put more effort into something that has, you know, transformative potential.

Dr. LEWIS. Yes, I would agree completely.

Mr. FOSTER. Things like laser-assisted launches, for example, you know, where you're beaming some of the power.

And so, what is your view of the most promising things there, if we have to place some bets on speculative technologies?

Dr. LEWIS. So, I actually do think, as Professor Epstein mentioned, air breathing to orbit. And the reason is it's not science fiction. We know how to build those engines, although we haven't gotten them quite up to the Mach numbers yet. And essentially, if you're air breathing to orbit, that means you're swallowing oxygen as you go, it simply means you're not carrying the oxygen in a tank onboard the vehicle. You don't have the massive tank. And there's several approaches you might try. One is the scramjet engines that I mentioned. The other, what are called liquid air cycle engines where you have a cryogenic fuel, very cold fuel. You condense air as you go, collect it, separate out the oxygen, and then burn that in a relatively conventional engine. I think that's quite promising as well.

I can go through the list of all the other options——

Mr. FOSTER. If you could just, you know, contact my office and if there's some reasonable number of pages to read on this, because we have to throw deep, deeper than we've been throwing, because you know, we don't want to have the ghost of Wernher Von Braun meeting us another 25 years from now.

Dr. LEWIS. I agree. If I may, you know, I think it was a Robert Heinlein quote that low Earth orbit is halfway to anywhere, and if we can get the cost down to low Earth orbit and make it more regular, possibly through aeronautic solutions, and I think it opens up tremendous things for space exploration as well.

Mr. FOSTER. All right. He had the physics right in the 1950s, I guess.

And so anyway, I'm out of time here, and thank you to all of the witnesses here, and I yield back.

Chairwoman HORN. Thank you, Mr. Foster, and thank you to all of our witnesses for being here today and for your testimony and insight.

Before we officially close the hearing, I want to say how much I appreciate the work that you're doing and your willingness to be here today as we move toward a NASA reauthorization, looking at the importance of the work that NASA Aeronautics is doing.

The record will remain open for 2 weeks for additional statements from the Members and for any additional questions the Committee may ask of the witnesses. The witnesses are excused and the hearing is now adjourned.

[Whereupon, at 4:39 p.m., the Subcommittee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Jaiwon Shin

NASA's Aeronautics Mission: Enabling the Transformation of Aviation
Questions for the Record from Chairwoman Horn

1. In May 2019, the NASA Advisory Council's Aeronautics Committee issued a finding to NASA on the University Leadership Initiative ULI in the Aeronautics Research Mission Directorate (ARMD). The finding emphasizes the need to assure diversity when selecting proposals and the importance of tracking metrics for participation demographics and also suggests implementing a policy or practice that would increase the participation rate of Historically Black Colleges and Universities (HBCUs). What is the participation rate in the ARMD ULI program of people of one or more underrepresented identities, HBCU s, and minority-serving institutions more broadly?

A: The University Leadership Initiative (ULI) has awarded 13 university-led teams in three rounds of ULI solicitations. These 13 teams are comprised of 47 universities and their industrial partners. Among the 47 universities, five of them are Historically Black Colleges and Universities (HBCUs) and six other universities are Minority Serving Institutions (MSIs). So, 11 of the 47 universities (23 percent) are either HBCU or MSI. Two of them are lead institutions:

- North Carolina A&T State University, a HBCU, is the lead university for their ULI award titled "Secure and Safe Assured Autonomy."
- Oklahoma State University, a MSI and #1 in the Nation among public land-grant colleges and universities for graduating Native American students, is the lead university for their ULI award titled "Real-time Weather Awareness for Enhanced Safety Assurance in Unmanned Aircraft System Traffic Management."

a. What specific language, if any, is included in ULI proposal calls to encourage diversity?

A: One of ULI's four strategic goals listed in the NASA solicitation is to

> *Promote greater diversity in aeronautics through increased participation of minority-serving institutions and underrepresented university faculties in ULI activities.*

To support this diversity goal, the solicitation includes (a) language that reinforces NASA expectations, and (b) "Teaming" evaluation criteria for proposers to understand that NASA will evaluate proposals to ensure ULI's diversity goal is met.

a) Language in the ULI solicitation reinforcing NASA expectations:

> *Building and applying a diverse, multi-disciplinary team is part of the strategic leadership role entrusted to awardees of this solicitation. ... Collaborations could include other departments at the PI's institution, other colleges or universities, industry members, non-profit organizations, or other U.S.-based entities. Undergraduate education programs could be incorporated. Historically Black Colleges and Universities (HBCU) and other minority-serving institutions (MSI) are strongly encouraged to participate. Proposers are expected to consider partnerships with schools that may have less prior experience in working on NASA Aeronautics research projects. Lead organizations can demonstrate leadership by creating mentoring opportunities, providing access to facilities or contacts, and otherwise helping to nurture and fully integrate the capabilities of less-established partners.*

ULI encourages special groups to increase their participation in this solicitation: female PIs, minority PIs, and new PIs. Each of these groups is crucial to making the national aeronautics research infrastructure healthy and reflective of the US.

Diverse partnerships are expected to bring a wealth of talent and different perspectives that can contribute to novel, innovative approaches. These benefits notwithstanding, proposers should not add members solely for the purpose of lengthening their partnership list. Each contributor should have a meaningful role.

b) The "Teaming" evaluation criteria used by NASA reviewers to assess submitted ULI proposals:

Innovative Teaming and Education (weighted at 20%)
- *Integrated team contributes to overall proposal strength.*
- *Innovative and inclusive teaming methods that promote diversity, mentoring of faculty from HBCU and/or other minority-serving institutions, and promoting education of the next generation of undergraduate and graduate engineers (see ULI Goals in Section D.4.1).*
- *Innovative training of student team members to become future leaders.*

The solicitation also states that *"Proposals without an appropriate involvement of HBCU or MSI will be rejected."*

2. How are the priorities for and balance within NASA's aeronautics research program and activities established?

A: NASA aeronautics research is guided by a compelling strategic vision. This strategy is the culmination of a multi-year effort that included gathering industry and other Government agencies' inputs, analyzing environmental and market trends, and identifying overarching societal factors. The trend analyses indicated that NASA could best contribute to the Nation's future societal and economic vitality by focusing on efforts that respond to a growing demand for mobility and to major challenges in energy efficiency and environmental sustainability while leveraging the convergence between traditional aeronautical disciplines and rapid technology advances in energy systems, additive manufacturing, and cyber-physical systems. Our investment strategy is outlined in the recently updated Strategic Implementation Plan, encompassing our vision for aeronautical research aimed at the next 25 years and beyond.

ARMD's research activities center around six strategic research thrusts:
- Thrust 1: Safe, efficient growth in global operations;
- Thrust 2: Innovation in commercial supersonic aircraft;
- Thrust 3: Ultra-efficient subsonic transports;
- Thrust 4: Safe, quiet, and affordable vertical lift air vehicles;
- Thrust 5: In-time, system-wide safety assurance; and
- Thrust 6: Assured autonomy for aviation transformation.

Each strategic thrust addresses an important area of research and technology development that will further U.S. leadership in the aviation industry and enhance safe, sustainable global mobility. NASA's research is performed with an emphasis on multi-disciplinary collaboration focused on critical, integrated challenges aligned to the six research thrusts. Together, these research thrusts combine to enable safe, sustainable growth in the overall global aviation system, while pioneering transformative capabilities that will create game-changing opportunities.

a. How does NASA engage the aeronautics stakeholder community in setting priorities and developing a program?

A: NASA Aeronautics has established direct and active partnerships with external organizations and other Federal agencies to ensure that we are investing in stakeholder-driven focus areas, bringing in the best ideas from the aeronautics community, enhancing the transfer of our research results to the broadest possible community, and maintaining accountability for results. Consultations with aeronautics community leaders during the establishment of new programs have ensured that we are focused on priority challenges, that our research activities are structured as effectively as possible, and that the community has clear visibility into our planning processes to support research collaboration in the future. For example, we have established an extensive community engagement approach for developing our research and demonstration plans for Advanced Air Mobility (AAM). This approach included community workshops on an AAM National Campaign (NC, formerly called UAM Grand Challenge) and on vehicle, operations, and community acceptance topics. We also hold focused workshops and roundtable discussions on contemporary challenges facing the industry through our NASA Aeronautics Research Institute (NARI) and in coordination with the National Academies of Sciences, Engineering, and Medicine (NASEM).

Our collaboration with the Federal Aviation Administration (FAA), one of our key partners, is embodied in Research Transition Teams (RTTs), which are designed to enhance progress for NextGen advancements in critical areas and effectively transition advanced capabilities to the FAA for certification and implementation. RTTs serve as the bridge between NASA's long term, game-changing research and technology and the FAA's near-term implementation research requirements. Under RTTs, NASA and the FAA develop joint research plans and fund their respective portions of the planned research according to the nature of the research, stage of research, and their relative capabilities.

Through open competition, we solicit and fund proposals for foundational research by academia, industry, and non-profit organizations via NASA Research Announcements (NRAs) to seek the best new ideas in support of ARMD strategic goals and research objectives. Awards through NRAs provide NASA researchers access to fresh ideas, leverage our funds by fostering collaboration between Government, industry and academia, and provide universities the opportunity to involve the next generation of engineers in working on today's aeronautics technical challenges. NRA-selected efforts often serve to identify the "trade space" related to a particular research topic, to identify solutions to particularly difficult problems, or to assist with technology transition.

During the execution stage, our research goes through an extensive peer review process, and external experts are central to our annual program reviews. We receive regular advice and assessment of our technical and management efforts from experts in industry, academia, and other Federal agencies. One such body is the Aeronautics Committee of the NASA Advisory Council (NAC), our chartered Federal Advisory Committee. We also have formalized and expanded our engagement with a broad range of community representatives through sponsorship of the Aeronautics and Space Engineering Board and the Aeronautics Research and Technology Round Table (ARTR) of the National Research Council (NRC). NASA engages extensively with the technical community through peer-reviewed publication of research and through participation in technical committees and conferences in partnership with a wide variety of professional technical associations.

b. How does NASA determine the relative balance in aeronautics research programs between fundamental and applied research?

A: NASA has developed a balanced portfolio, focusing on priority technical challenges in our research missions to provide those new ideas and technologies which can be matured and graduated into our systems-level research activities. At the base is strategically-driven foundational research to advance concepts and technology development for key aviation challenges and opportunities. The long-term nature of these investments enables NASA Aeronautics to systematically develop knowledge, methods, and the basic feasibility of technologies. We focus investments on specific Technical Challenges which have the greatest potential for impact to solve the most pressing aviation challenges. To inform our technical challenges and complement our in-house NASA research, NASA funds collaborative research through NASA Research Announcements with industry and academia and cutting-edge research through the NASA University Leadership Initiative.

The most promising technologies are further matured and incorporated into integrated systems research. In integrated systems research, NASA brings together individual components to ensure that they perform in an integrated manner as well as they did when developed individually. Given the scale of the experimentation required in this type of research, we must be very selective and ensure close partnership with the aeronautics community in the research process. This ensures that we leverage partner investments, and maximize the potential for technology transition into the air transportation system or into the fleet. Through systems and market analysis and stakeholder consultation, we determine which technologies NASA is uniquely able to advance at a pace and scale that will have the greatest impact on aviation, focusing on high-risk, high-payoff research that would not be conducted by the private sector. By maturing new technologies and validating design methods, NASA research reduces the risk of incorporating new technologies and systems in aircraft, shortening the path through safety certification in the FAA, and speeding the transition of new technologies into the fleet.

3. The first and to-date, only National Academies' Decadal Survey of Civil Aeronautics, was published in 2006. Do you plan to engage the Academies in another decadal survey in civil aeronautics? If so, when? If not, why not?

A: NASA has a robust strategy and strategic implementation plan (SIP) developed in extensive consultation with the external stakeholder community. Instead of commissioning another decadal survey across the entirety of civil-aviation-related research topics, NASA has worked closely with the National Academies to commission focused research studies on priority research topics aligned with the SIP. These studies constitute a potential national research agenda to address critical community needs. The results consist of prioritized research activities of importance to the national and international commercial aeronautics community with a focus on advances in technologies and capabilities that can be achieved through substantial research and technology development. So far the National Academies have completed studies on Low Carbon Propulsion, Autonomy, In-Time System Wide Safety, and Advanced Air Mobility. The National Academies also published a study on recapturing NASA's Aeronautics Flight Research Capabilities which has helped to inform our approach to integrated systems demonstration as part of our balanced research portfolio. In addition, the NRC has convened focused meetings of experts on our behalf to review and provide advice on new activities in formulation. NASA intends to build on the success of these targeted assessments that have been of great value in establishing community research priorities to address national challenges instead of commissioning another more general decadal survey.

4. One of the stated goals of the Urban Air Mobility (UAM) Grand Challenge is to promote public confidence in UAM safety. How do you plan to use the technology demonstrations to bolster public confidence?

A: The UAM Grand Challenge has been redesignated as the AAM National Campaign (NC). NASA currently is working with the FAA, AAM vehicle developers, and airspace management system providers to identify AAM technologies and concepts that need to be developed, matured, and demonstrated in a series of progressively more challenging national campaigns. Industry will bring their vehicles and airspace system technologies to NASA facilities, or potentially fly at their own locations, and fly safety scenarios with real and simulated traffic. Through these flights, they will evaluate their ability to overcome key safety and integration barriers across AAM vehicle and airspace systems, and identify critical operational challenges remaining to be solved. The first set of NC tests will focus on AAM operational scenarios, including contingencies. These scenarios will progress in complexity through the NC series as Industry technologies develop, likely requiring higher levels of vehicle and airspace system automation or autonomy to complete.

The NASA NC series will facilitate bringing together vehicle and airspace service providers to help understand the current AAM system maturity levels with respect to vehicle performance, safety assurance, airspace interoperability, etc., and to develop and demonstrate integrated solutions for civil use. NASA will work with a variety of partners across several local and regional use cases, but scalable urban use cases are the expected NC end state.

Safety and operational data gathered during the NC can be used to inform industry consensus standards and provide the basis for FAA safety certification of AAM vehicles, systems, and operations. NASA will promote community awareness of NC goals and progress and solicit input on community challenges through a robust ecosystem consultation mechanism that was established this spring; this mechanism will be leveraged to build confidence in AAM safety.

5. Will the data from the Low Boom Flight Demonstration (LBFD) mission be shared with the broader aviation community and the public?

A: Yes, the purpose of the Low Boom Flight Demonstrator (LBFD) mission is to gather of data on public perception regarding supersonic overflight and acceptable sonic boom noise levels for these flights. The data resultant from these experimental flights will be provided to the Federal Aviation Administration (FAA) and the International Civil Aviation Organization (ICAO) so that these governing bodies can set future noise standards for supersonic flight over land. The provided data would be publicly available.

6. While sonic boom reduction is often cited as a key enabler of commercial supersonic aircraft, there have been continuing concerns about the impacts of future supersonic aircraft on the ozone layer and the climate.

a. How significant are the environmental impacts?

A: Future commercial supersonic aircraft would fly at altitudes higher than commercial subsonic aircraft do today, putting their emissions in closer proximity to the layers of the upper atmosphere. NASA, our fellow Federal agencies, and our partners recognize that it is important to anticipate and address this future emissions challenge. NASA is working with the FAA and Massachusetts Institute of Technology (MIT) to more completely understand the nature and significance of supersonic, high-altitude emissions.

b. What will need to be done to address them, and what, if any, efforts in NASA Aeronautics are underway in this area?

A: NASA is leveraging research and investment for subsonic engine emissions reductions and identifying the unique technical challenges for supersonic engine emissions. Technologies originally developed to reduce the emissions of engines for subsonic aircraft are being assessed for applicability to engines for supersonic aircraft. Many of these approaches and technologies appear to be of potential benefit to future commercial supersonic engines. Additionally, NASA has been advancing and evaluating the effects of sustainable alternative jet fuel use in these advanced systems. Such fuels are not manufactured from petroleum, but from renewable feedstocks, therefore having an overall lower life-cycle carbon contribution. Additionally, NASA is supporting the international aviation regulatory community by developing computer-based models of future supersonic aircraft and engines that can be used to estimate future emissions and inform the setting of regulatory standards. These models will also help inform how much additional research will be needed in the future.

7. NASA's X-57 Maxwell test aircraft will be fully electric. After being tested and demonstrated in FY 2020, how will NASA proceed to transfer the technology to industry? When does NASA anticipate we would see this technology gain widespread use in commercial aviation, either through hybrid gas-electric or fully electric aircraft?

A: NASA is already transferring the technology and lessons learned to industry as the project progresses. X-57 testing and development continues, although it has been delayed due to the impacts of COVID-19 and associated restrictions to on-site access to NASA facilities. However, NASA already has released extensive data from X-57 research into high voltage all-electric powertrains through a series of mechanisms including technical papers and presentations, posting materials online, and through meetings and discussions with interested representatives of industry, academia, other Government agencies, and technical standards development organizations. These data ultimately will provide a basis for certification standards of electric bus architectures and enable vehicle developers to make design decisions based on a common, non-proprietary knowledge base. NASA personnel are currently participating on standards committees that are addressing the certification of electrified aircraft systems. This work, and the wide dissemination of electrified aircraft research data, will continue throughout the life of the X-57 project. Battery research and associated development for X-57 has already been transitioned to industry as a product. In addition, there is extensive research and product development currently ongoing in industry utilizing other electrified aircraft systems technologies, but it is outside the scope of NASA's work to predict when industry would commercially implement some or all of these technologies.

8. What research is NASA currently conducting to advance the transition in commercial aviation to wider use of biofuels? What are the primary limiting factors to transition?

A: NASA historically has worked with other Government agencies and organizations domestically and internationally to characterize the environmental benefits of "drop-in" sustainable alternative jet fuels (also known as biofuels). Such fuels are not manufactured from petroleum, but from renewable feedstocks, therefore having an overall lower life-cycle carbon contribution. NASA's contributions included measuring the emissions of these fuels from actual aircraft engines both on the ground and in flight. Data resulting from these tests has been used as input to air quality and climate change models and has informed the development of aviation emission standards. NASA also has worked on advanced combustor concepts that will operate efficiently and effectively on sustainable alternative fuels as well as traditional petroleum-based jet fuel. NASA research continues to advance the physics-based understanding of combustion and combustion processes as a foundation for ensuring that future aircraft systems can take full advantage of the environmental benefits offered by alternative jet fuels. The factors limiting more extensive use of biofuels in aviation are primarily related to alternative fuel feedstock development, production and distribution, which are outside the scope of NASA's research mandate.

9. Under the proposed transfer of the Aeroscience Evaluation and Test Capabilities Project (AETC), how can the Aeronautics Research Mission Directorate ensure sufficient access to the wind tunnels for aeronautics testing and research?

A: The Aerosciences Evaluation and Test Capabilities (AETC) Portfolio is within the Aeronautics Research Mission Directorate (ARMD), per the appropriated FY 2020 budget. AETC continues to operate as an Agency portfolio, stewarding the large aerosciences ground test facilities for use by all four Mission Directorates as needed to accomplish their missions. AETC consults with Mission Directorate representatives through the Aerosciences Test Advisory Board (ATAB), as well as with external users, to identify ground test requirements and priorities and deconflict competing requirements as necessary. Additionally, AETC representatives are invited to participate in ARMD strategic planning discussions to provide them with insights into ARMD research and testing priorities. Through continued extensive coordination and planning, AETC is able to ensure sufficient access to portfolio assets for ARMD and other users.

a. What is the operational status and condition of NASA's aeronautical facilities today, such as wind tunnels?

A: The condition of NASA facilities varies, but most of the facilities are quite old and require continuing maintenance and attention. NASA is working to ensure that all critical aeroscience facilities are operational and available to meet the Nation's missions. To keep the portfolio of aeroscience test facilities operating successfully, the AETC budget covers a combination of operational test requirements, maintenance, and capability upgrades. AETC maintains a comprehensive risk-to-test assessment of the facility components and systems in the maintenance backlog across this portfolio. The purpose of this risk-to-test assessment is to ensure that maintenance funding is allocated to the highest priority maintenance needs and repairs with the most significant impact on NASA's mission.

b. What, if any, improvements to existing facilities or new facilities are needed to enable the transformation of aviation going forward?

A: AETC is constantly assessing potential improvements or new aeroscience test capability investments required to support NASA's current and future priority research. AETC currently is investing in wind tunnel facility capability advancements such as higher speed, higher fidelity data acquisition systems, more efficient and more accurate wind tunnel and model control systems, new test environment and simulation ability, and more robust facility operational systems. A recent example includes the need for the NASA 9' x 15' Low Speed Wind Tunnel to reduce the test section background acoustic signal caused by air flowing through the tunnel. The previous background acoustic levels in the 9' x 15' test section had made it increasingly difficult to test newer and quieter aircraft engine technologies. AETC conducted major modifications to the tunnel that now allows sufficient separation between the aircraft engine acoustic signal and the test section background acoustic signal. AETC also invests in new test technologies to improve measurement capabilities (pressure, force, flow, and temperature) as well as new test techniques and processes. These investments result in test capabilities deemed critical to meeting NASA research needs and applicable to a variety of wind tunnel facilities. AETC is working with NASA mission directorates to evaluate the accuracy and efficiency of computational fluid dynamics (CFD) simulation compared to wind tunnel testing to inform future decisions about ground test and simulation needs.

As ARMD develops new air vehicle concepts and technologies, new facilities are sometimes needed to test these technologies, either within or outside of the AETC portfolio. For example, to support research into megawatt-scale electrified aircraft propulsion, NASA developed the NASA Electric Aircraft Testbed (NEAT) facility at Glenn Research Center to test electrified aircraft propulsion architectures and systems at flight-altitude conditions. This first-of-a-kind research facility (not included in AETC) has been used by NASA and industry to conduct groundbreaking research on megawatt-class electrified propulsion architectures, supporting U.S. leadership in this new technology. NASA will continue to invest in new facility capabilities required to advance aerospace technology as those needs are identified.

10. What data is NASA gathering to inform potential future regulations for Urban Air Mobility (UAM) vehicles?

A: NASA is working with the FAA and the broader community to determine the data needed to inform future regulations. NASA is developing the NC and associated research agenda with the intent of delivering a UAM system architecture and corresponding requirements and guidelines for a safe and scalable UAM transportation system. Current AAM planning is focused on:

- **Vehicle Development and Operations -** Develop concepts and technologies to define requirements and standards addressing key challenges such as safety, affordability, passenger acceptability, noise, automation, etc.
- **Airspace Design and Operations -** Develop Unmanned Aircraft System (UAS) Traffic Management (UTM)-inspired concepts and technologies to define requirements and standards addressing key challenges such as safety, access, scalability, efficiency, predictability, etc.
- **Community Integration -** Create robust implementation strategies that provide significant public benefits and catalyze public acceptance, local regulation, infrastructure development, insurance and legal frameworks, etc.

11. How have the two-market studies NASA commissioned and released in November 2018 on Urban Air Mobility (UAM) informed NASA's research and development plans for UAM?

A: NASA has been assessing the viability of the AAM sector through market studies and other scientific assessments for some time. Market, technology, and infrastructure studies, combined with focus groups, have helped to develop an understanding of key challenges to be addressed by NASA and accelerate the industry. Industry organizations undertake their own proprietary market studies tailored to their specific products and services. The NASA studies are more broadly available to support public understanding of market trends, opportunities for future demand across various use cases, and associated technological and policy barriers affecting future market developments. The studies also have enabled NASA to establish a new Advanced Air Mobility Project to inform this emerging market by addressing barriers associated with vehicle development and operations, airspace design and operations, and community integration.

a. Why did the two studies come to different conclusions about the feasibility of a UAM air taxi market?

A: The future market study conclusions are dependent upon the documented assumptions about the technology and policy barriers to AAM adoption and subsequent expert assessment of market demand. Since this is an entirely new aviation sector, it is not surprising that there is variability among these assessments, but overall, both market studies tell a consistent story that UAM missions are viable and can change the aviation landscape. The value of these market studies is to gain aviation expert assessments of the trade space, trends and factors influencing future demand, and future market viability, as opposed to the prediction of a specific level of future demand for a particular use case. NASA is focused on developing enabling technology that will support multiple use cases.

12. Dr. Kroo's prepared testimony noted that many people and organizations even within the

aeronautics community have little idea of what NASA is doing and has done in aeronautics. How do you and your team communicate the return on investment and role of NASA's Aeronautics Research Mission Directorate to the aeronautics community and the American taxpayers more broadly?

A: NASA actively seeks to inform and educate stakeholders, the aviation community, and the public on what we are doing through a variety of means. NASAs research results are widely disseminated through publications and presentations in technical journals and papers throughout the United States and the world. We hold conferences and workshops to engage with industry and academia about our research strategies and results, and develop partnerships with leading manufacturers, service providers, airlines and Government agencies to conduct research and transition the results into practice. We staff exhibits at major aviation technical conferences to interact with researchers and with the next generation of aerospace workers. We offer an Aeronautics Research series of books on key technical projects that can be downloaded at no cost. NASA Aeronautics also works every day to inform and educate the public on the benefits and progress of our work through news media articles, frequent and impactful social media campaigns, webinars, free content including a vast array of science, technology, engineering, and mathematics (STEM) learning activities on NASA.gov, video programs on NASA TV and YouTube, and other methods. NASA Aeronautics' dedicated social media platforms (@NASAaero) currently have more than 100,000 followers, and we just launched a moderated Facebook group for aeronautics educators with currently 300-plus members. Based on the dissemination of our research results and benefits, and quantitative evidence of our ability to engage broad audiences through these many venues, we understand that there is broad understanding of NASA's aeronautics research portfolio. As a Federal research agency, we need to maintain the appropriate balance of investment in research and development (R&D) and external public outreach, but we are always looking for new opportunities to strategically communicate our benefits in an impactful way.

13. What are the results from NASA's Advanced Composites Project, and what, if any, further work is NASA planning on composites?

A: The Advanced Composites Project (ACP) was an effort within ARMD from FY 2014-2019 to improve methods, tools, and technologies that shorten the time required to develop and certify composite aircraft structures. Under the ACP, research was focused on three areas: accurate strength and life prediction, rapid inspection and characterization, and efficient manufacturing process development. Among many individual technology development and transition successes, the ACP demonstrated a more-than-20-percent reduction in the time needed to develop and certify advanced composite structures for aircraft applications. Key outcomes include:

- ACP delivered validated high-fidelity methods to predict the onset and progression of damage in composite aircraft structures.
- ACP developed non-destructive evaluation (NDE) technologies for rapid inspection of complex composite structures.
- New computer-based methods and models to relate manufacturing parameters to defect formation were developed under the ACP and incorporated into commercial design and analysis software.
- Technologies developed by the ACP were transferred to industry and university partners by their participation in collaborative research tasks and to the external technical community through more than 400 conference papers and archival journal publications. Software developed was distributed to U.S. industry through open-source release and incorporated into commercial software distributed by license.

- ACP research results were incorporated into the FAA-sponsored, industry-standard reference *Composite Materials Handbook-17*, a repository of proven reliable engineering information and standards to support the development and use of composite materials and structures.

One of the keys to the success of the ACP was its use of a teaming approach, with NASA, the FAA, industry, and academia working together in a public-private partnership called the Advanced Composites Consortium (ACC). Members of the consortium successfully executed 24 collaborative research activities, with multi-member sharing of costs and resulting intellectual property.

NASA recognizes that continued advances in materials, structures and manufacturing (MSM) technologies are needed in order for the U.S. aviation industry to remain competitive and address the worldwide demand for both conventional transport aircraft as well as potential future aircraft such as AAM vehicles. Over the last year, NASA has been developing a holistic strategy for MSM to guide future research investments. NASA investments would be made strategically across the Mission Directorate, and would appropriately leverage public-private partnerships with industry, NASA Research Announcements with industry and academia, and university research grants through NASA's University Leadership Initiative.

14. During the question and answer period of the hearing, you stated that, in the area of hypersonics, NASA could "certainly increase the partnerships with other government agencies." How might the NASA Aeronautics Research Mission Directorate increase partnerships with other agencies in hypersonics? Please also discuss any NASA partnerships with university/academia on hypersonics research.

A: NASA currently has a robust partnership with the Department of Defense (DoD) in hypersonics, with each party contributing its respective capabilities and expertise to benefit each agency's unique mission. NASA continues a stable investment in unique, specialized facilities and experts who conduct fundamental research to address key challenges in hypersonic flight. NASA coordinates closely with partners in the DoD to leverage their investments in ground and flight activities and to access research data from these tests. Such data is important to developing and validating advanced physics-based computational models as building blocks towards a long-term vision for hypersonic flight. At the same time, the DoD benefits from extensive access to NASA hypersonics expertise, analyses, testing capabilities, and computational models both through collaborative and reimbursable research activities. NASA is in regular communication and coordination with DoD regarding opportunities for future collaboration on mutually beneficial research supporting NASA's own mission requirements. NASA is also working with academia to build the future hypersonics workforce, including funding a number of research studies and fellowships for graduate students in the hypersonics area. NASA is coordinating with the Air Force Office of Scientific Research (AFOSR) on a hypersonics-related proposal topic for the NASA ULI this year, as well.

15. During the question and answer period of the hearing, you stated that the agency management has more details on additional hiring authorities NASA may need to attract the next generation aeronautics workforce. Could you please share those details?

A: NASA's workforce continues to be its greatest asset for enabling missions in space and on Earth. NASA has one of the highest average lengths of service in the Federal government. We don't see that as a weakness. Instead, we see our multi-generational workforce as one of NASA's greatest strengths. NASA employees – regardless of age – cite shared values, commitment to the mission, and loyalty to NASA as reasons why they feel positively about their jobs and why they stay at NASA. This low attrition rate, however, does mean we have less opportunity to use attrition as a natural lever for rebalancing skillsets in order to meet changing mission requirements and fast-paced technological advances. Therefore, it would be helpful to have more flexibility in how we hire and retain people, especially for certain skilled workers who are in great demand in the private sector.

NASA senior leaders are working on a multi-year, overarching strategy that will provide more agility across our overall workforce, including strategic skills planning and talent mobilization. Additionally, NASA continues to work with the Office of Personnel Management (OPM) on acquiring flexible talent management and hiring authorities. In late 2019, for example, OPM granted NASA Direct Hire Authority, which authorizes NASA to hire up to 4,500 General Schedule (GS) employees over five years, as part of NASA's plan to return astronauts to the Moon in 2024.

NASA's Aeronautics Mission: Enabling the Transformation of Aviation
Questions for the Record from Mr. Charlie Crist

1. Commercial aviation is key to U.S. exports and international competitiveness, with aerospace manufacturing resulting in $151 billion in export sales in 2018. The U.S. aerospace sector employs over 500,000 Americans and remains an economic and workforce success stories. However, there is more international competition than ever and that is expected to grow significantly in the decades ahead. As the industry looks to address this challenge, how can NASA's X-Plane program help support the types of innovative concepts that will ensure the U.S. remains at the leading edge of commercial aviation?

A: Flight demonstrations and flight experiments are critical and costly final steps before full-scale commercial development, building on technology development and assessment using simulations and ground-based tests. NASA can play an important role partnering with industry to address this challenge by researching and maturing individual technologies in the laboratory and through ground tests, and then integrating and demonstrating them in a relevant flight environment. NASA has done this in recent years, culminating in demonstration of landing gear noise reduction and advanced wing technologies using NASA research aircraft. Additionally, by leveraging the Boeing EcoDemonstrator aircraft, NASA has demonstrated advanced aircraft tail, wing, and engine nacelle acoustic liner technologies, as well as flight deck traffic management technologies. NASA's research in developing an all-electric, general aviation size experimental airplane - the X-57 Maxwell - already is delivering to the community important lessons about designing, building, and operating an all-electric system. X-57 ground tests this year and flight tests next year will provide valuable insights into the challenges and opportunities of electric aircraft and serve as the building blocks for industry to create future safe and certifiable aircraft designs. The X-59 Quiet SuperSonic Technology (QueSST) aircraft will uniquely provide community response data critical to changing international regulations to support commercial supersonic flight over land. Looking ahead, NASA intends to build on this experience in partnership with industry by further demonstrating advanced technologies in flight using NASA and industry assets.

2. What do you believe is the next step in commercial aviation technologies? How can a subsonic X-Plane program at NASA help enable the development, testing, and flight testing of these key technologies?

A: Through technical advances by NASA and industry in the coming years, it is likely that future large commercial aircraft may look different, may be powered differently, may be made from different materials, and may even be designed and manufactured differently. Large leaps in aircraft efficiency coupled with reductions in noise and harmful emissions are critical to the environmental sustainability of aviation. NASA is collaborating with U.S. industry to investigate innovative technology for subsonic aircraft such as advanced configurations and wing design, small core turbine engines, and transformative lightweight structures using high-rate composite manufacturing. NASA also is leading research into new components, technologies and powertrain architectures for electric and hybrid-electric propulsion systems that can bring about revolutionary improvements in small and large transport aircraft. NASA recently completed single-aisle transport aircraft concept studies with industry to develop hybrid gas-electric propulsion concepts and assess their potential benefits for larger vehicles, such as regional transports and airplanes as large as a Boeing 737. Building on these activities, NASA has begun a multi-year effort to solve the technical challenges of a 1-Megawatt-(MW)-power electric propulsion system – enough energy to power 165 homes. NASA will refine concepts and technologies and validate new electric and hybrid electric propulsion systems through ground and flight tests. By maturing these technologies to Technology Readiness Level 6 by the mid- to late-2020s and demonstrating them in flight, U.S.

manufacturers will be in a position to further mature them to the point of commercialization in the next generation of large single-aisle transport aircraft to be introduced in the early 2030s.

3. As companies make investments in passenger and cargo autonomous air vehicles, how we can we ensure this becomes a successful export market similar to commercial aircraft? Are we are doing everything we can at NASA, the FAA, and other federal government agencies to ensure the U.S. takes the lead in this emerging global market opportunity?

A: NASA is a leader in creation of an Advanced Air Mobility or AAM system that is safe, economical, and environmentally friendly to move people and packages in population centers, forever changing how citizens around the world benefit from aviation. AAM vehicles can range from small delivery drones to passenger-carrying air vehicles that have electrically-powered Vertical Take Off and Landing (eVTOL) capability. We want American companies to build these vehicles and systems, and sell them to the world.

NASA began a new Advanced Air Mobility project in FY 2020 to enable the emergence of Urban Air Mobility (UAM) and support a strong U.S. industrial base. NASA is enhancing Unmanned Aircraft System (UAS) Traffic Management (UTM) and UAS capabilities developed at NASA for application to AAM operations and developing concepts for safe AAM operations. Countries around the world are basing their regulatory frameworks governing small UAS operations on the NASA-developed UTM framework, and we are poised to play the same global leading role for AAM, enabling a safe and level playing field for U.S. AAM companies to compete globally.

NASA is preparing a series of "National Campaigns" that will provide a means to assess the maturity of key systems for UAM. Through these National Campaigns, NASA will serve as a catalyst for companies to rapidly develop and demonstrate their capabilities on U.S. soil, while setting the course for research and investment needed to realize the full potential of AAM and supporting the development of standards and regulations for AAM vehicles and systems. Research to reduce noise and improve efficiency and safety of vertical lift vehicles also is supporting development of this fledgling industry. NASA's National Campaign efforts already include partnerships with many of the leading domestic companies in AAM. The Federal Aviation Administration (FAA) has worked closely with NASA at the working and executive levels in building the NASA AAM portfolio; the FAA also is working directly with domestic industry leaders for AAM. Through extensive community outreach and industry consultation, NASA is facilitating understanding of the challenges and solutions of AAM among Federal, state, and local governments, industry, academia, and the public, thereby fostering U.S. community acceptance and early adoption of AAM.

NASA's Aeronautics Mission: Enabling the Transformation of Aviation
Questions for the Record from Mr. Michael Waltz

1. Dr. Shin: One of the greatest challenges we face in aviation is the need for more civil air pilots and aircraft maintenance technicians to support a growing global commercial aviation industry. Embry-Riddle University in Daytona Beach, Florida, is leading the world in this space. Recently, Boeing and Embry-Riddle University announced a new $3 million scholarship programs to increase the number of veterans, women and minority students pursuing careers in this sector. What role can NASA play to help encourage more students to pursue careers as pilots and technicians? How do we encourage more workforce development and scholarship programs to meet this demand, like the one Boeing and Embry-Riddle have announced?

A: NASA is focused on establishing visionary goals for the future aviation system and on research and development of technologies to enable future aircraft and airspace systems to support that vision. Our work inspires students to engage in the aviation sector to achieve that shared vision for the future.

2. Dr. Shin: Your testimony lays out how NASA's infrastructure and expertise enable our nation's hypersonics program. Other agencies fund hypersonics at much higher levels than NASA; however, NASA has unique facilities and expertise in the field. Is there an opportunity for NASA to expand its work with the Department of Defense? Would greater access to NASA facilities or expertise aid DOD in hypersonics development?

A: NASA currently has a robust partnership with the Department of Defense (DoD) in hypersonics, with each party contributing its respective capabilities and expertise to benefit each agency's unique mission. NASA continues a stable investment in unique, specialized facilities and experts who conduct fundamental research to address key challenges in hypersonic flight. NASA coordinates closely with partners in the DoD to leverage their investments in ground and flight activities and to access research data from these tests. Such data is important to developing and validating advanced physics-based computational models as building blocks towards a long-term vision for hypersonic flight. At the same time, the DoD benefits from extensive access to NASA's hypersonics expertise, analyses, testing capabilities and computational models both through collaborative and reimbursable research activities. For FY 2020, NASA currently projects receiving approximately $35.0M from the DoD for reimbursable work in hypersonics. NASA is in regular communication and coordination with DoD regarding opportunities for future collaboration on mutually beneficial research supporting NASA's own mission requirements. This regular communication also includes coordination on access to NASA facilities and expertise.

3. Dr. Shin: As you may know, China and Russia have partnered to develop a new commercial aircraft and China's state-owned aerospace manufacturer has ambitious plans for the commercial aircraft market in the years ahead. Given the importance of the global market to U.S. exports of commercial aircraft, what is NASA doing to ensure that the U.S. industry remains competitive and is supporting R&D in the most critical technology areas for the next several decades?

A: NASA has developed a balanced portfolio focused on high-priority technical challenges in our research mission areas. This focus provides new ideas and technologies which can be matured and potentially graduated into more complex, systems-level research activities. At the base of this balanced research portfolio is strategically driven foundational research to advance concepts and technology development for key aviation challenges and opportunities. The long-term nature of these investments enables NASA Aeronautics to systematically develop knowledge, methods, and the basic feasibility of technologies. We focus investments on overcoming specific Technical Challenges that have the greatest potential for impact on the most pressing aviation challenges. To inform our efforts and complement our research, NASA funds collaborative research through NASA Research Announcement awards with industry and academia and cutting-edge academic research through the NASA University Leadership Initiative.

The most promising of these technologies can be further matured and considered for integrated systems research. Through integrated systems research, NASA brings together individual components to ensure that they perform as well when integrated as they did when developed individually. Given the scale of the experimentation required in this type of research, we must be very selective and ensure close partnership with the aeronautics community in the research process. This approach ensures that we leverage partner investments and maximize the potential for technology transition into the fleet. Through systems and market analyses, as well as stakeholder consultation, we determine which technologies NASA is uniquely able to advance at a pace and scale that will have the greatest impact on aviation. In doing so, NASA focuses on high-risk, high-payoff research that would not be conducted by the private sector. By maturing new technologies and validating physics-based design methods, NASA can reduce the risk of incorporating new technologies and systems in aircraft, shorten the path through safety certification in the FAA, and speed the transition of new technologies into the fleet.

Specific to large commercial aircraft, NASA is collaborating with U.S. industry to investigate innovative technologies for subsonic aircraft, such as advanced configurations and wing design, small core turbine engines, and transformative structures using high-rate composite manufacturing. NASA also is leading research into new components, technologies and powertrain architectures for electric or hybrid electric propulsion systems that can bring about revolutionary improvements in small and large transport aircraft. By maturing these technologies to Technology Readiness Level 6 by the mid- to late-2020s and demonstrating them in flight, U.S. manufacturers will be in a position to further mature them to the point of commercialization in the next generation of large civil transports to be introduced in the early 2030s.

Through this comprehensive research strategy, NASA will foster the continued U.S. leadership of the global aerospace industry.

Responses by Dr. Alan H. Epstein

1

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE AND AERONAUTICS
NASA's Aeronautics Mission: Enabling the Transformation of Aviation
Dr. Alan H. Epstein
Submitted by Chairwoman Horn

1. How do the NASA Aeronautics Research Mission Directorate (ARMD) priorities and program align with community consensus recommendations from the National Academies?
a. What do you see as the general value of a decadal survey for aeronautics? Is another decadal survey for aeronautics needed, and, if so, why?

2. What is the value of NASA's wind tunnels to the aviation and aeronautics community?
a. How do NASA's aeronautics test facilities compare to those available in industry or in other countries?

b. Do you have any comment on NASA's proposal to transfer the management of the wind tunnels and other facilities in the Aeroscience Evaluation and Test Capabilities Project (AETC) from the Aeronautics Research Mission Directorate to the Mission Support Directorate?
c. What, if any, improvements to existing facilities are needed to enable the transformation of aviation going forward?

3. How do the NASA Aeronautics Research Mission Directorate (ARMD) priorities and program align with community consensus recommendations from the National Academies?

4. In 2009, you were a witness before· this subcommittee in a hearing on biojet fuels. You spoke of the potential of biofuels to reduce net emissions while maintaining engine performance. It's now ten years later; has this potential been realized? Why or why not? What more needs to be done?

5. Dr. Kroo's prepared testimony noted that many people and organizations even within the aeronautics community have little idea of what NASA is doing and has done in aeronautics. Do you share Dr. Kroo' s concerns? If so, what might be potential solutions?

6. You noted in your prepared testimony that suburban and even rural areas might also be serviced by "urban" air mobility (UAM). How would the approach or research objectives to enable UAM in suburban or rural areas differ from research to support UAM deployment in cities?
a. What are the unique advantages and disadvantages of rural air mobility as it compares to urban air mobility?

Q1. How do the NASA Aeronautics Research Mission Directorate (ARMD) priorities and program align with community consensus recommendations from the National Academies?
a. What do you see as the general value of a decadal survey for aeronautics? Is another decadal survey for aeronautics needed, and, if so, why?

Reply:
As background - NASA ARMD interacts with the ASEB in four venues:

1. Semi-annual ASEB meetings - experts from industry, academia, and nonprofits,
2. Semi-annual Executive Roundtable meetings - leaders from industry, academia, and nonprofits,
3. Workshops as requested – typically a one or two-day assembly of experts discussing a specific issue for which a written proceeding may be issued,
4. Ad-hoc committees –groups of experts assembled under the purview of the ASEB to address detailed questions, whose reply is in the form of a formal, written, peer-reviewed report, issued typically 12-18 months after a contract is approved. Only ad-hoc committees issue formal findings and recommendations to a sponsor.

In my eight years associated with ASEB or its committees, I have observed that NASA has consistently used its informal interactions at meetings of the ASEB and the Executive Roundtable to discuss new programs and directions. I note that NASA presentations at subsequent meetings often reflected the board/committee comments and inputs on the topic at prior meetings. Similarly, the recommendations of ad-hoc committee reports are clearly reflected in subsequent ARMD actions and plans. These reports typically result in a written reply/commentary from ARMD. So, in the last decade the National Academies – ARMD interactions have been impactful.

Decadal surveys have been very valuable for the NASA Space Science community in prioritizing scientific objectives and the missions needed to achieve them. However, the total ARMD budget is usually smaller than that of the smallest of the Space Science divisions, Heliophysics. In the past few years, the PBR for ARMD has been small enough that some activities/areas were arguably on life-support to preserve the capability for the nation.

A decadal survey for aeronautics at NASA could be useful if there are sufficient operational funds for discretionary action. Such a report could help set priorities and even assist in triage should budget realities dictate such action. It would be more useful if the ARMD budget as planned for out years is sufficient to support more extensive programs such as X-planes.

Q2. What is the value of NASA's wind tunnels to the aviation and aeronautics community?
a. How do NASA's aeronautics test facilities compare to those available in industry or in other countries?
b. Do you have any comment on NASA's proposal to transfer the management of the wind tunnels and other facilities in the Aeroscience Evaluation and Test Capabilities Project (AETC) from the Aeronautics Research Mission Directorate to the Mission Support Directorate?
c. What, if any, improvements to existing facilities are needed to enable the transformation of aviation going forward?

Reply:
Background - Large wind tunnels are essential national assets for both aeronautical research and product development. NASA shares with DoD stewardship of this nation's wind tunnels and aeronautical test facilities. These are used by NASA, DOD, and private industry. These assets – substantial, costly structures – are of little value without experienced staff and adequate instrumentation and test equipment. All of this is costly to buy, to maintain, and to operate. A large tunnel can cost thousands to tens of thousands of dollars per operating hour. Over the years, various business models have been used. The most destructive is full cost accounting, in which a facility's entire annual operating budget is allocated across whoever uses it that year. A year with few users drives up the cost per hour to the point that few wish to or can afford to use it, which drives down utilization, which drives up user cost. This can be a death spiral for a facility. Thankfully, ARMD moved away from this accounting model a few years ago.

a) Simply put, the wind tunnel infrastructure in the U.S. is ancient, with many of the larger facilities over 60-80 years old. Although there has been some modernized over the years, these are still antiquated. US industry closed many of its facilities in the last few decades, victims of industry consolidation and full cost accounting. U.S. industry mainly uses NASA, DoD and European facilities as needed for product development. The European facilities often have higher productivity since they were built relatively recently making use of lessons learned in the US. ARMD has managed its facilities as national assets, giving priority at times to the needs of DoD and industry.

b) NASA's proposal to transfer the management of the wind tunnels and other facilities in the Aeroscience Evaluation and Test Capabilities Project (AETC) from the ARMD to the Mission Support Directorate would seem to make sense from an overall NASA management perspective. Some caution is warranted, however, since aeronautical facilities are only one part of the NASA infrastructure that needs modernization. ARMD represents only 3% of the NASA budget, but its impact on the US economy is disproportionately much, much more significant. So, a concern with the proposed reorganization is whether due attention will be paid to aeronautical facilities maintenance and upgrades. Congressional oversight would be helpful.

c) This is a excellent, timely question, especially given the exciting new emerging areas. A thoughtful answer would require a comprehensive study. Perhaps this is an area for future ASEB activity

Q3. How do the NASA Aeronautics Research Mission Directorate (ARMD) priorities and program align with community consensus recommendations from the National Academies?

Reply:
Please see the reply to question 1, above.

Q4. In 2009, you were a witness before this subcommittee in a hearing on biojet fuels. You spoke of the potential of biofuels to reduce net emissions while maintaining engine performance. It's now ten years later; has this potential been realized? Why or why not? What more needs to be done?

Reply:
Over the past decade, we have learned how to make sustainable alternative jet fuel (SAJF) using several processes and from a variety of feedstocks. "Sustainable" means that it does not adversely affect the food supply, water, etc. Plant based processes (biofuels) are just one of the many feedstocks now possible. SAJF is now made from waste vegetable oils and fats, trash, as well as waste plant material such as stover. Feedstocks such as stover may be particularly attractive in that it can generate additional income for farmers with no impact on food production. Extensive ground and flight testing have proven these fuels to be safe and effective. The life cycle reduction in CO_2 emission can be 80% or more compared to petroleum-based conventional fuel. Currently, hundreds of millions of gallons of SAJF are produced annually. For example, all flights out of LAX are made partially on SAJF. However, this volume represents less than 1% of the world's annual jet fuel consumption.

The biggest challenge is cost. The economics of SAJF must justify the investment needed to build and operate the facilities. Of course, the cost of conventional jet fuel reflects that of petroleum, which is quite volatile and has proven resistant to accurate prediction. At the moment, petroleum prices are low, so SAJF investments are less attractive.

Congress can help in several ways:

a. Encourage research that brings down the cost of SAJF production. NASA has no role to play here but the Departments of Energy and Agriculture may.
b. Ensure that any future legislation addressing climate change and CO_2 give appropriate credit to SAJF as a low net CO_2 energy source.
c. Explore avenues to encourage investments in SAJFs.

5. Dr. Kroo's prepared testimony noted that many people and organizations even within the aeronautics community have little idea of what NASA is doing and has done in aeronautics. Do you share Dr. Kroo' s concerns? If so, what might be potential solutions?

Reply:
There are undoubtedly many students today who are unaware that NASA is a currently a lead in aeronautics research, and fewer still who care about what was done decades ago. They know NASA for space - astronauts and compelling pictures from probes. I believe that there are two contributors to this. First, ARMD represents only three percent of the NASA budget. I do not know what fraction of the communications and media work of NASA is about aeronautics, but it is certainly much, much less than that for space. Second, there is much less compelling activity in aeronautics, so there is less to talk about, even if much of what does go on is about making peoples' lives better. Moreover, frankly, I do not find paper studies of airplanes and pictures of wind tunnel models very exciting compared to astronauts broadcasting from space and images from planetary probes.

Innovative, advanced airplanes really flying, i.e., X-planes, do generate considerable excitement but have been largely missing from ARMD activities for the last few decades (model airplanes with X numbers do not really count). Going forward, I would expect and hope that a new era of X-planes would generate considerable excitement.

Why is knowledge of and excitement about aeronautics essential for the nation? The US is the world's leader in aviation products and services, which represent our largest manufactured export. This dominance was built over the last century by some of the most talented scientists and engineers the world has ever seen. We cannot continue to dominate, or even compete well, without a continual stream of young technical talent entering the business. Young people need to be excited about airplanes and flying. NASA ARMD and headquarters can make significant contributions to generating that excitement.

6. You noted in your prepared testimony that suburban and even rural areas might also be serviced by "urban" air mobility (UAM). How would the approach or research objectives to enable UAM in suburban or rural areas differ from research to support UAM deployment in cities?
a. What are the unique advantages and disadvantages of rural air mobility as it compares to urban air mobility?

Reply:
Urbanization in this country drives up land and housing prices, clogs highways, and strains services in large cities. At the same time, rural areas are suffering from loss of population, especially young people, and declining services and opportunities. Excessive travel time to services and work adds to rural isolation. One approach to reducing isolation could be massive highway construction. A much less expensive and capital-intensive approach could be personal air mobility vehicles. Helicopters have proven to be much, much too expensive and too noisy to be of practical value here. Many new automated, electric or hybrid-electric concepts being explored for UAM have the potential to drop operating cost, significantly reduce noise, and, because they would be produced in much larger numbers, reduce acquisition cost. Peoples' time in rural America is just as valuable as that of urbanites. Significantly reducing travel time among rural communities and between rural communities and urban areas has the potential to expand rural residents' access to jobs, medical care, education, and shopping. Of course, the same capability would be valuable to people living in the suburbs and exurbs of metropolitan areas, perhaps helping to relieve commuting congestion.

Comparing rural air mobility (RAM) with urban air mobility (UAM) is thought provoking. RAM is about moving fewer people longer distances than UAM. Assuming one is interested in solutions that serve more than just the rich, cost is an important issue for both. The influence of perhaps fewer passengers on each leg must be considered. Also, poor weather may be more important for RAM since the geographical area served and the trip duration will be greater. Production volume is a significant determinate of cost. Since most people live in cities now, RAM will likely be a smaller market. Can one design or set of technologies serve both UAM and RAM markets?

So, compared to operations in urban areas, one might expect vehicles optimized for rural operations to favor longer ranges and higher speeds, perhaps at the expense of increased noise and recharge/refuel times. Operation in marginal weather will be more important, but congested airspace less so. How these differing requirements are reflected in research tasks and priorities should be approached thoughtfully and deliberately. ARMD recently commissioned the ASEB for a detailed study on UAM. One approach to addressing this question would be to add a rural air mobility task addressing the questions such as the above.

Second Set of Questions

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE AND AERONAUTICS
NASA's Aeronautics Mission: Enabling the Transformation of Aviation
Questions for the Record to:
Dr. Alan H. Epstein
Submitted by Mr. Crist

1. Commercial aviation is key to U.S. exports and international competitiveness, with aerospace manufacturing resulting in $151 billion in export sales in 2018. The U.S. aerospace sector employs over 500,000 Americans and remains an economic and workforce success stories. However, there is more international competition than ever -and that is expected to grow significantly in the decades ahead. As the industry looks to address this challenge, how can NASA's X-Plane program help support the types of innovative concepts that will ensure the U.S. remains at the leading edge of commercial aviation?

2. What do you believe is the next step in commercial aviation technologies? How can a subsonic X-Plane program at NASA help enable the development, testing, and flight testing of these key technologies?

3. As companies make investments in passenger and cargo autonomous air vehicles, how we can we ensure this becomes a successful export market similar to commercial aircraft? Are we doing everything we can at NASA, the FAA, and other federal government agencies to ensure the U.S. takes the lead in this emerging global market opportunity?

Q1. Commercial aviation is key to U.S. exports and international competitiveness, with aerospace manufacturing resulting in $151 billion in export sales in 2018. The U.S. aerospace sector employs over 500,000 Americans and remains an economic and workforce success stories. However, there is more international competition than ever -and that is expected to grow significantly in the decades ahead. As the industry looks to address this challenge, how can NASA's X-Plane program help support the types of innovative concepts that will ensure the U.S. remains at the leading edge of commercial aviation?

Reply:
While commercial aviation is a primary industrial sector for the US, it is relatively concentrated in terms of industry players and their products. The large industrial enterprises that dominate airplane production and their first-tier suppliers often produce only a few distinct products, a half dozen airplane types and associated engines for example. Each of these requires billions or tens of billions to bring to market and represent the work of tens of thousands of workers. Even for a very large corporation, a significant product misstep can be devastating and may not be readily survivable. As we have seen recently, even the temporary grounding of an otherwise sound product can cost billions and measurably affect the US economy. The consequences of failure at this level are reflected in an industry-wide aversion to technical risk, or perhaps what a business person might regard as excessive risk.

NASA X-planes can help break through this conservatism at least four ways. The first is to significantly reduce technical risk to the point that an industrial enterprise can consider product development with reasonable risk. By generating data in a realistic environment (NASA's Technology Readiness Level 6), flying is especially useful for maturing technology and identifying unanticipated challenges. Second, X-planes reduce business risk by demonstrating to the entire commercial aviation ecosystem – airplane producers, their suppliers, regulators, and airlines purchasers– that a new concept is feasible. These people must risk their businesses on a new concept. As a supplier CEO once said to me about a promising, proposed technology, "I'll believe it when I see it flying." Third, it gives local communities assurance that aviation is working to improve community concerns including noise and emissions. Fourth, importantly, X-planes can inspire new generations to consider a career in aviation.

The key to all of this, of course, is a thoughtful and timely selection of the right problem to solve and demonstrate. In the past decade, NASA ARMD has done an excellent job of listening to industry and understanding where the US industrial base would like to go. An X-plane program can be an opportunity to drive industry in new directions further and faster than it would otherwise go, generating new value for this nation and capturing a competitive edge.

Q2. What do you believe is the next step in commercial aviation technologies? How can a subsonic X-Plane program at NASA help enable the development, testing, and flight testing of these key technologies?

Reply:

Background - I believe that the most significant impediment to the expansion of US commercial air travel is noise. Local communities oppose new airports or airport expansion to avoid the associated disruptions. The most significant threat to aviation's long-term future is climate change and associated public perception. (In fact, in this country, air commercial air travel emits less CO_2 per passenger-mile than do cars or trains.) Over the past decade or so, NASA sponsored a series of studies to explore the possibilities for dramatic emissions reductions, especially CO_2. Several concepts were identified with the promise of improvements on the order of 50%-70% compared with the reference late 1990's designs. The configurations of these airplanes differ significantly from legacy airliners. The associated uncertainty over technology risk and public acceptance are significant hurdles to adoption. An X-plane could be of great help here.

Research earlier in this century by MIT and the University of Cambridge found that airliners could be envisioned that are so quiet that they would not be noticed in an urban environment. Their research also suggested that many of the features that contribute to noise reduction also improve fuel consumption and thus CO_2. Such virtually silent aircraft would bring enormous relief to communities and stimulate the expansion of air travel. It would also obsolete many legacy designs. Noise generation of new configurations in flight is challenging to assess accurately without flying, so an X-plane would be an appropriate approach.

Assuming NASA can support only one airliner X-plane program at a time, I would suggest that the desired and achievable requirements for a 2030 product launch be carefully considered. How important are the relative attributes of cost, noise, and emissions in that time frame and beyond? An ASEB study could be of help here.

Q3. As companies make investments in passenger and cargo autonomous air vehicles, how we can we ensure this becomes a successful export market similar to commercial aircraft? Are we doing everything we can at NASA, the FAA, and other federal government agencies to ensure the U.S. takes the lead in this emerging global market opportunity?

Reply:
The very real likelihood of autonomous air vehicles will be the most exciting, and perhaps economically impactful, aeronautics development of the last several decades. There appear to be several hundred players around the world hoping to capture segments of this market. Historically, the strengths of the US have included an entrepreneurial industry, a large domestic market, academia supplying enthusiastic and educated young people, a modest amount of government-supported, precompetitive advanced research (NASA & DoD), and the world's most respected regulator (the FAA). NASA supports the FAA on the research side, specifically in regards to air traffic control and some aspects of safety, but it does not work on certification issues. Both the FAA and NASA are working on autonomous air vehicles related challenges.

The FAA tries to balance the need for innovation in aircraft design against assurances of safety. It does not have the in-house expertise to thoroughly evaluate all new technologies, given the constraints on FAA workforce and resources. Some have felt strongly that the in the past FAA has overly constrained the introduction of new technologies; others believe it hasn't done enough. My concern in this area is given the current intense focus on the FAA's possible role in the recent airline tragedies, that the natural tendency for a regulator would be to move toward conservatism in their assessments. Other counties' regulators may not feel the same pressure and so permit their industries to move faster.

I am unable at this time to comment on the questions: is the Federal government doing enough, or too much, are agency actions sufficiently coordinated? This may be a good question for the ASEB to consider. I will point out that in Congress, NASA and the FAA fall under the purview of different committees. At the National Academies, they fall under different boards. So, this question may warrant a coordinated, integrated study.

Responses by Dr. Mark Lewis

NASA's Aeronautics Mission: Enabling the Transformation of Aviation

Answers to Questions for the Record to:

Dr. Mark J. Lewis

from Chairwoman Horn:

1. the NASA Aeronautics Research Mission Directorate priorities and program are well aligned to community consensus and recommendations from the National Academies. The portfolio truly covers a wide scope of topics within aviation, including subsonic fixed wing, supersonic, and rotorcraft. ARMD has also led the Agency in its support of university research, again matching the consensus interests. The emphasis on green aviation, improved air traffic control, safety, and autonomous operations all reflect the aerospace community's general top priorities, with one exception. In years past hypersonics was managed as a separate area within ARMD, but it is no longer. That has made hypersonics less visible and helped contribute to its diminished emphasis. It would be good to see a separate hypersonics portfolio broken out again and properly supported.

a. I don't see significant value in performing another aeronautics decadal survey. The Academies' decadal process has been extremely valuable for the space science community, where there are so many competing interests and possible paths forward. The same process has less value for the aeronautical engineering world, where there is already consensus and more obvious research directions.

2. I do share Dr. Kroo's concerns, the first "A" in NASA often receives less attention than the space part of the agency. The best solution would be for NASA itself to place greater emphasis on telling this part of its story, via its website, promotional materials, PR efforts, etc. It would be good if the aviation industry did a better job of crediting NASA's contributions as well.

3. NASA's wind tunnels are absolutely essential for a healthy American aerospace research portfolio. It isn't just the physical infrastructure, but the people and their expertise as well that are national assets.

a. NASA's facilities are generally ageing, but still among the very best in the world. Among the examples I cited in my testimony, the Langley 8-ft is the premier high speed engine test cell in the U.S.

b. I am less concerned about how NASA manages its tunnels as opposed to NASA continuing to manage its tunnels, and not using an organizational shift as an excuse to decommission national facilities.

c. The Langley 8-ft tunnel is scheduled for a nozzle upgrade, and that is essential. I have heard that the Langley Unitary Tunnel facility may be decommissioned, and that would be a dreadful mistake from which the community could not recover, and I would encourage

Congress to intervene if necessary. I would also strongly encourage the recommissioning of the Plum Brook Hypersonic Test Facility (HTF) – for a modest investment the national could have a highly capable high-speed engine test cell.

4. NASA has the correct priorities with their X-59 supersonic demonstrator, though I am concerned that only one plane will be built, and that the timelines for its construction are rather extended – it should not take more than two years to build an X-plane. History has shown that X-plane programs are best done with at least two vehicles, and preferably three. I would also encourage NASA to do a full-scale X-plane for advanced transport concepts – moving away from standard tube and wing designs with more efficient blended-wing geometries, building on the previous X-48 subscale craft. Such concepts could be the future of commercial aviation, and NASA can play a role in ensuring American leadership. I would also encourage NASA to partner with the USAF on X-60, the hypersonics flight test bed, and use it as a "wind tunnel in the sky" for a range of flight experiments in the high-speed realm.

5. I really know of only two main ways to reach orbit with airbreathing engines – scramjets and liquid air cycle engines. Work on scramjets is well documented but the liquid-air systems are less well known. In the liquid-air concepts, a heat exchanger is used to condense air as the vehicle flies and collect liquid oxygen, then use that oxygen for combustion in a relatively conventional engine. The concept can also be used to deeply cool the air entering an engine, essentially tricking that engine into behaving as if it were flying at a lower speed. The lead in this area is a British company, Reaction Engines, https://www.reactionengines.co.uk, which has proven very eager to partner with the U.S. even establishing a subsidiary in Colorado that is doing very impressive test and development work.

From Mr. Crist:

1. I could not agree more that commercial aviation is key to U.S. exports and competitiveness! By their very nature, X-planes are designed as engineering experiments, allowing us to probe the limits of flight. I draw a strong distinction between X-planes and "demonstrators," with the latter being used to prove something that we think we already know, whereas the former is an important part of the scientific process. NASA should be considering a series of X-planes that would serve as flying test beds for such things as advanced subsonic airliner and cargo aircraft – moving away from conventional tube-and-wing designs. A good start would be an X-plane that builds on the subscale X-48, but at full scale. The supersonic X-59 flight test bed is also a good start, but NASA needs to accelerate the timelines and build more craft in the series in order to be able to accept more risk. NASA should also work with the USAF on a high-speed X-plane, perhaps partnering with the Air Force Research Lab on its planned X-60 hypersonic flight test bed.

2. The challenge in predicting the next step in aviation is that today's commercial aircraft are amazing machines – pushing the absolute limits of efficiency and performance. A modern jet aircraft is one of, perhaps THE, most efficient machine ever built, using nearly all of the

energy available in its fuel to provide useful transportation. Directions for future developments would include advanced designs that move away from standard tube-and-wing shapes, following blended wing concepts. NASA should invest in a full-scale blended wing program to explore not only the aerodynamic performance issues, but practical operations and ergonomics as well. Another area for investment is advanced propulsion. A modern gas turbine engine is designed to operate optimally at only a single design point, yet there are new concepts that would allow for a broader operating range that NASA should explore.

3. With a budget that represents only about 3% of the total NASA investment, only a fraction of that being devoted to commercial aviation, and relatively modest investments in other agencies, it is hard to argue that we are doing all we can to support America's dominance in this area.

From Mr. Waltz

1. There is definitely an opportunity for NASA to expand its work with the Department of Defense in hypersonics. NASA has already proven to be a critical partner in both past programs (X-51, HIFiRE) and planned efforts (DARPA's HAWC). NASA has unique capabilities, not only in its physical infrastructure, but in the knowledge of its research staff and the work it sponsors in industry and academia. NASA has already made its facilities available to DOD researchers and their contractors but there is a serious backlog. Recommissioning the Plum Brook HTF tunnel would be of great value to our nation's efforts. I would also recommend against decommissioning the Langley Unitary facility.

In addition, it would be great to see NASA renewing its investment in fundamental hypersonics, including its work with universities. This is something that NASA is uniquely positioned to do in the federal government, and would be a valuable addition to our efforts to build knowledge and an expanded workforce in the hypersonics arena. Ideally this would be coordinated with the DOD agencies that sponsor fundamental work in the field, including AFOSR and ONR.

Appendix II

ADDITIONAL MATERIAL FOR THE RECORD

LETTER SUBMITTED BY REPRESENTATIVE KENDRA HORN

AIA AEROSPACE INDUSTRIES ASSOCIATION

July 1, 2019

Rep. Eddie Bernice Johnson, Chair
House Committee on Science, Space
and Technology
2321 Rayburn House Office Building
Washington, D.C. 20515

Rep. Frank D. Lucas, Ranking Member
House Committee on Science, Space
and Technology
H2-394 Ford House Office Building
Washington, DC 20515

Rep. Kendra Horn, Chair
Subcommittee on Space and Aeronautics
House Committee on Science, Space
and Technology
2321 Rayburn House Office Building
Washington, D.C. 20515

Rep. Brian Babin, Ranking Member
Subcommittee on Space and Aeronautics
House Committee on Science, Space
and Technology
H2-394 Ford House Office Building
Washington, DC 20515

Dear Chairwoman Johnson, Ranking Member Lucas, Chairwoman Horn and Ranking Member Babin:

The Aerospace Industries Association (AIA) appreciates the opportunity to submit our position on the importance of NASA's aeronautics mission and applauds the House Science, Space and Technology Committee's Subcommittee on Space and Aeronautics for holding today's hearing: "NASA's Aeronautics Mission: Enabling the Transformation of Aviation." We are pleased to see that this Committee is prioritizing NASA aeronautics particularly at a time when NASA is performing critical research projects that will impact the future of aviation.

AIA is the voice of the American aerospace and defense industry. We represent nearly 340 leading aerospace and defense manufacturers and suppliers, supporting 2.5 million jobs and over $150 billion in annual exports. Our industry relies on NASA's research to help integrate new industry technologies into the National Airspace System (NAS), improve aircraft environmental performance and sustainability, and enhance the safety and efficiency of aviation.

Since the Wright Brothers' first flight in 1903, aeronautics has been a pillar of American innovation and international competitiveness. NASA and its predecessor, the National Advisory Committee for Aeronautics, have pioneered new technologies that helped aviation evolve from a niche form of transportation into an affordable form of mass travel with unrivalled safety and efficiency.

Aviation is expected to grow rapidly in the coming decades, and aeronautical breakthroughs will be necessary to ensure we can accommodate new vehicles safely and sustainably into our airspace. One of the ways that NASA helps expand the horizon for new innovative technologies is through X-plane experimental development and testing.

The X-1 was the first manned aircraft to break the sound barrier. More than 60 years later, the X-59 is now driving the reemergence of supersonic flight. The low-boom technology equipped on the aircraft will significantly reduce the infamous boom associated with the Concorde and open the door to a sustainable future for supersonic travel. With continuing support and innovation from industry, NASA, and other government agencies, supersonic flight will soon become a reality.

Another NASA X-plane, the X-57 all-electric aircraft, will help the next generation of jetliners achieve radical breakthroughs in environmental performance and build on the incredible progress to date, where current aircraft are already 85% more fuel efficient and producing 75% less noise than the first generation.

NASA's aeronautics work is also directly driving innovation that will change aviation as fundamentally as the invention of the jet engine. This includes work on Unmanned Aircraft Systems (UAS). Integrating these new aircraft into the sky will require a new form of traffic management for aircraft operating below 400 feet altitude. This system, called UAS Traffic Management (UTM), was initiated as a NASA research project. Once fully implemented, it will unlock the potential of UAS in the NAS and allow new markets and public service opportunities to take place at scale, including package delivery and emergency medical evacuation operations.

In addition, NASA is actively researching how to properly integrate Urban Air Mobility (UAM) concepts into the NAS through its recently announced UAM Grand Challenge. UAM will change the way people move in urban areas and connect to rural areas. It will also relieve the stress on our existing surface infrastructure like roads and bridges by providing alternatives to traditional ground transportation. Once completed, the UAM Grand Challenge will provide critical data to inform how UAM aircraft will integrate and operate in the NAS.

While taking a UAM aircraft to work or having a drone deliver a package to your door may seem like something out of the Jetsons, NASA's research has made this plausible in the near future for the aviation industry. And with continued investment, these advancements in aviation will have a profound impact on how we travel and explore our world.

As this Committee considers a long-term bill reauthorizing the National Aeronautics and Space Administration this year, we urge you to give a priority to NASA's aeronautics research programs, including the following elements:

- Authorize fundamental subsonic aeronautics research and technology within the next two decades to ensure U.S. leadership in the global aerospace market;

- Authorize technology development for civil supersonic air travel that reduces sonic booms to acceptable levels to communities and informs FAA regulatory decision-making in supersonic flight;

- Authorize hybrid-electric, airframe and advanced propulsion technologies to enable significant improvements in travel speed, energy efficiency, and reduced noise and emission levels;

- Authorize research projects related to UAS, UAM and UTM to help enable full integration of these technologies into the NAS in a timely manner and ensure U.S. leadership in this increasingly competitive global market; and

- Direct NASA to submit an updated comprehensive, five-year plan for the aeronautics program that lays out a roadmap for basic science and engineering research, investment in key NASA facilities, and specific X-plane demonstrations.

We thank the Subcommittee for bringing attention to this critical matter and look forward to working with Congress to provide NASA with the authority and funding it needs to bring critical research to life in the years to come. If you have questions or need further information about our positions, please contact me at (703) 358-1000 or at David.silver@aia-aerospace.org.

Sincerely,

David Silver
Vice President - Civil Aviation
Aerospace Industries Association of America

ARTICLE SUBMITTED BY REPRESENTATIVE BRIAN BABIN

The New York Times Magazine | https://nyti.ms/2L0EiLt

AT WAR

Hypersonic Missiles Are Unstoppable. And They're Starting a New Global Arms Race.

The new weapons — which could travel at more than 15 times the speed of sound with terrifying accuracy — threaten to change the nature of warfare.

By R. Jeffrey Smith

June 19, 2019

This article is a collaboration between The Times Magazine and the Center for Public Integrity, where R. Jeffrey Smith is the managing editor for national security.

On March 6, 2018, the grand ballroom at the Sphinx Club in Washington was packed with aerospace-industry executives waiting to hear from Michael D. Griffin. Weeks earlier, Secretary of Defense James Mattis named the 69-year-old Maryland native the Pentagon's under secretary for research and engineering, a job that comes with an annual budget of more than $17 billion. The dark-suited attendees at the McAleese/Credit Suisse Defense Programs Conference were eager to learn what type of work he would favor.

The audience was already familiar with Griffin, an unabashed defender of American military and political supremacy who has bragged about being labeled an "unreconstructed cold warrior." With five master's degrees and a doctorate in aerospace engineering, he was the chief technology officer for President Reagan's Strategic Defense Initiative (popularly known as Star Wars), which was supposed to shield the United States against a potential Russian attack by ballistic missiles looping over the North Pole. Over the course of his career that followed, he wrote a book on space vehicle design, ran a technology incubator funded by the C.I.A., directed NASA for four years and was employed as a senior executive at a handful of aerospace firms.

Griffin was known as a scientific optimist who regularly called for "disruptive innovation" and who prized speed above all. He had repeatedly complained about the Pentagon's sluggish bureaucracy, which he saw as mired in legacy thinking. "This is a country that produced an atom bomb under the stress of wartime in three years from the day we decided to do it," he told a congressional panel last year. "This is a country that can do anything we need to do that physics allows. We just need to get on with it."

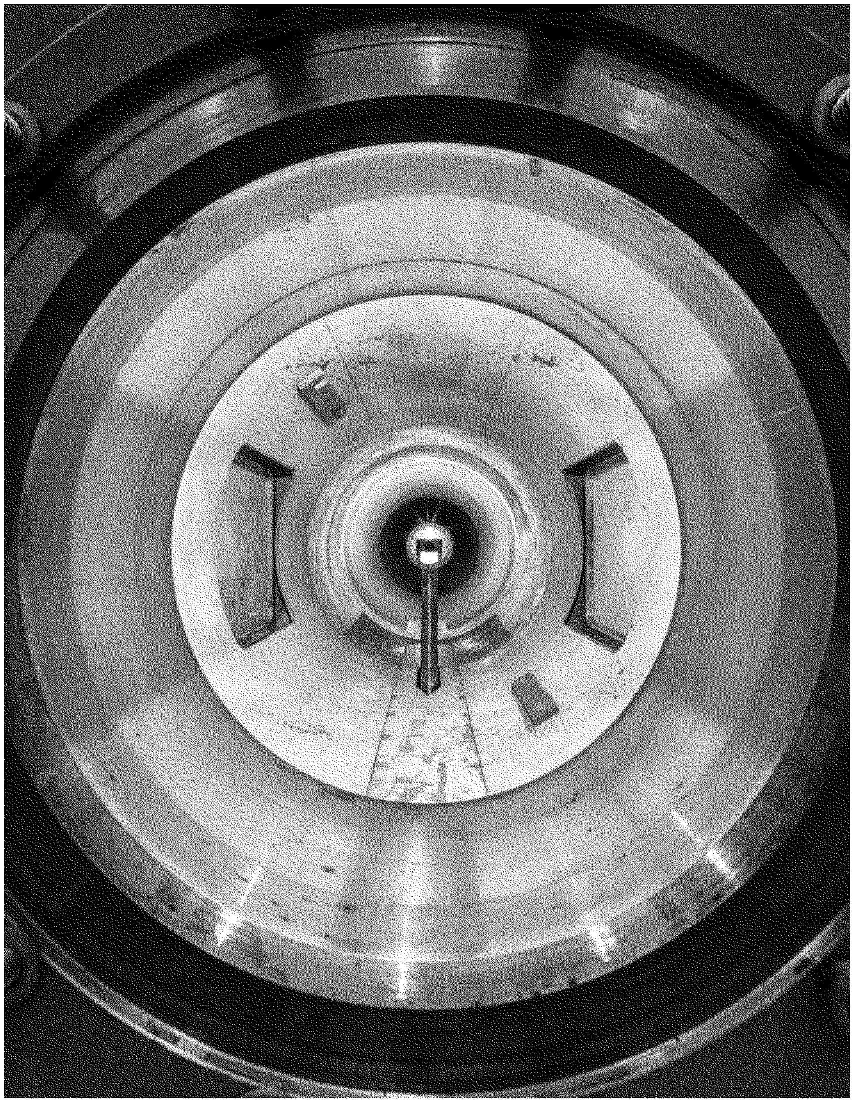
In recent decades, Griffin's predecessors had prioritized broad research into topics such as human-computer interaction, space communication and undersea warfare. But Griffin signaled an important shift, one that would have major financial consequences for the executives in attendance. "I'm sorry for everybody out there who champions some other high priority, some technical thing; it's not that I disagree with those," he told the room. "But there has to be a first, and hypersonics is my first."

Griffin was referring to a revolutionary new type of weapon, one that would have the unprecedented ability to maneuver and then to strike almost any target in the world within a matter of minutes. Capable of traveling at more than 15 times the speed of sound, hypersonic missiles arrive at their targets in a blinding, destructive flash, before any sonic booms or other meaningful warning. So far, there are no surefire defenses. Fast, effective, precise and unstoppable — these are rare but highly desired characteristics on the modern battlefield. And the missiles are being developed not only by the United States but also by China, Russia and other countries.

[*To follow the development of hypersonic missiles and other military technology, sign up for the weekly At War newsletter.*]

Griffin is now the chief evangelist in Washington for hypersonics, and so far he has run into few political or financial roadblocks. Lawmakers have supported a significant expansion of federal spending to accelerate the delivery of what they call a "game-changing technology," a buzz phrase often repeated in discussions on hypersonics. America needs to act quickly, says James Inhofe, the Republican senator from Oklahoma who is chairman of the Armed Services Committee, or else the nation might fall behind Russia and China. Democratic leaders in the House and Senate are largely in agreement, though recently they've pressed the Pentagon for more information. (The Senate Armed Services Committee ranking member Jack

Reed, a Democrat from Rhode Island, and House Chairman Adam Smith, the Democratic representative for Washington's ninth district, told me it might make sense to question the weapons' global impact or talk with Russia about the risks they create, but the priority in Washington right now is to get our versions built.)



Interior of the high-velocity wind tunnel in White Oak, Md., where scientists are testing hypersonic missile prototypes. Dan Winters for The New York Times

In 2018, Congress expressed its consensus in a law requiring that an American hypersonic weapon be operational by October 2022. This year, the Trump administration's proposed defense budget included $2.6 billion for hypersonics, and national security industry experts project that the annual budget will reach $5 billion by the middle of the next decade. The immediate aim is to create two deployable systems within three years. Key funding is likely to be approved this summer.

The enthusiasm has spread to military contractors, especially after the Pentagon awarded the largest one, Lockheed Martin, more than $1.4 billion in 2018 to build missile prototypes that can be launched by Air Force fighter jets and B-52 bombers. These programs were just the beginning of what the acting defense secretary, Patrick M. Shanahan, described in December as the Trump administration's goal of "industrializing" hypersonic missile production. Several months later, he and Griffin created a new Space Development Agency of some 225 people, tasked with putting a network of sensors in low-earth orbit that would track incoming hypersonic missiles and direct American hypersonic attacks. This isn't the network's only purpose, but it will have "a war-fighting capability, should it come to that," Griffin said in March.

Development of hypersonics is moving so quickly, however, that it threatens to outpace any real discussion about the potential perils of such weapons, including how they may disrupt efforts to avoid accidental conflict, especially during crises. There are currently no international agreements on how or when hypersonic missiles can be used, nor are there any plans between any countries to start those discussions. Instead, the rush to possess weapons of incredible speed and maneuverability has pushed the United States into a new arms race with Russia and China — one that could, some experts worry, upend existing norms of deterrence and renew Cold War-era tensions.

Although hypersonic missiles can in theory carry nuclear warheads, those being developed by the United States will only be equipped with small conventional explosives. With a length between just five and 10 feet, weighing about 500 pounds and encased in materials like ceramic and carbon fiber composites or nickel-chromium superalloys, the missiles function like nearly invisible power drills that smash holes in their targets, to catastrophic effect. After their launch — whether from the ground, from airplanes or from submarines — they are pulled by gravity as they descend from a powered ascent, or propelled by highly advanced engines. The missiles' kinetic energy at the time of impact, at speeds of at least 1,150 miles per hour, makes them powerful enough to penetrate any building material or armored plating with the force of three to four tons of TNT.

They could be aimed, in theory, at Russian nuclear-armed ballistic missiles being carried on trucks or rails. Or the Chinese could use their own versions of these missiles to target American bombers and other aircraft at bases in Japan or Guam. Or the missiles could attack vital land- or sea-based radars anywhere, or military headquarters in Asian ports or near European cities. The weapons could even suddenly pierce the steel decks of one of America's 11 multibillion-dollar aircraft carriers, instantly stopping flight operations, a vulnerability that might eventually render the floating behemoths obsolete. Hypersonic missiles are also ideal for waging a decapitation strike — assassinating a country's top military or political officials. "Instant leader-killers," a former Obama administration White House official, who asked not to be named, said in an interview.

Within the next decade, these new weapons could undertake a task long imagined for nuclear arms: a first strike against another nation's government or arsenals, interrupting key chains of communication and disabling some of its retaliatory forces, all without the radioactive fallout and special condemnation that might accompany the detonation of nuclear warheads. That's why a National Academies of Sciences, Engineering and Medicine report said in 2016 that hypersonics aren't "simply evolutionary threats" to the United States but could in the hands of enemies "challenge this nation's tenets of global vigilance, reach and power."

The arrival of such fast weaponry will dangerously compress the time during which military officials and their political leaders — in any country — can figure out the nature of an attack and make reasoned decisions about the wisdom and scope of defensive steps or retaliation. And the threat that hypersonics pose to retaliatory weapons creates what scholars call "use it or lose it" pressures on countries to strike first during a crisis. Experts say that the missiles could upend the grim psychology of Mutual Assured Destruction, the bedrock military doctrine of the nuclear age that argued globe-altering wars would be deterred if the potential combatants always felt certain of their opponents' devastating response.

And yet decision makers seem to be ignoring these risks. Unlike with previous leaps in military technology — such as the creation of chemical and biological weapons and ballistic missiles with multiple nuclear warheads — that ignited international debate and eventually were controlled through superpower treaty negotiations, officials in Washington, Moscow and Beijing haven't seriously considered any sort of accord limiting the development or deployment of hypersonic technology. In the United States, the State Department's arms-control bureau has an office devoted to emerging security challenges, but hypersonic missiles aren't one of its core concerns. Secretary of State Mike Pompeo's deputies say they primarily support making the military's arsenal more robust, an unusual stance for a department tasked with finding diplomatic solutions to global problems.

This position worries arms-control experts like Thomas M. Countryman, a career diplomat for 35 years and former assistant secretary of state in the Obama administration. "This is not the first case of a new technology proceeding through research, development and deployment far faster than the policy apparatus can keep up," says Countryman, who is now chairman of the Arms Control Association. He cites examples of similarly "destabilizing technologies" in the 1960s and 1970s, when billions of dollars in frenzied spending on nuclear and chemical arms was unaccompanied by discussion of how the resulting dangers could be minimized. Countryman wants to see limitations placed on the number of hypersonic missiles that a country can build or on the type of warheads that they can carry. He and others worry that failing to regulate these weapons at the international level could have irreversible consequences.

"It is possible," the United Nations Office of Disarmament Affairs said in a February report, that "in response [to] the deployment of hypersonic weapons," nations fearing the destruction of their retaliatory-strike capability might either decide to use nuclear weapons under a wider set of conditions or simply place "nuclear forces on higher alert levels" as a matter of routine. The report lamented that these "ramifications remain largely unexamined and almost wholly undiscussed."

[*Only 5 Nations Can Hit Any Place on Earth With a Missile. For Now.*]

So why haven't the potential risks of this revolution attracted more attention? One reason is that for years the big powers have cared mostly about numerical measures of power — who has more warheads, bombers and missiles — and negotiations have focused heavily on those metrics. Only occasionally has their conversation widened to include the issue of strategic stability, a topic that encompasses whether specific weaponry poses risks of inadvertent war.

An aerospace engineer for the military for more than three decades, Daniel Marren runs one of the world's fastest wind tunnels — and thanks to hypersonics research, his lab is in high demand. But finding it takes some time: When I arrived at the Air Force's White Oak testing facility, just north of Silver Spring, Md., the private security guards only vaguely gestured toward some World War II-era military research buildings down the road, at the edge of the Food and Drug Administration's main campus. The low-slung structure that houses Marren's tunnel looks as if it could pass for an aged elementary school, except that it has a seven-story silver sphere sticking out of its east side, like a World's Fair exhibit in the spot where an auditorium should be. The tunnel itself, some 40 feet in length and five feet in diameter, looks like a water main; it narrows at one end before emptying into the silver sphere. A column of costly high-tech sensors is grafted onto the piping where a thick window has been cut into its midsection.

Marren seemed both thrilled and harried by the rising tempo at his laboratory in recent months. A jovial 55-year-old who speaks carefully but excitedly about his work, he showed me a red brick structure on the property with some broken windows. It was built, he said, to house the first of nine wind tunnels that have operated at the test site, one that was painstakingly recovered in 1948 from Peenemünde, the coastal German village where Wernher von Braun worked on the V-2 rocket used to kill thousands of Londoners in World War II. American military researchers had a hard time figuring out how to reassemble and operate it, so they recruited some German scientists stateside.

As we entered the control room of the building that houses the active tunnel, Marren mentioned casually that the roof was specially designed to blow off easily if anything goes explosively awry. Any debris would head skyward, and the engineers, analysts and visiting Air Force generals monitoring the wind tests could survive behind the control room's reinforced-concrete walls.

Inside the main room, Marren — dressed in a technologist's polo shirt — explained that during the tests, the tunnel is first rolled into place on a trolley over steel rails in the floor. Then an enormous electric burner is ignited beneath it, heating the air inside to more than 3,000 degrees, hot enough to melt steel. The air is then punched by pressures 1,000 times greater than normal at one end of the tunnel and sucked at the other end by a vacuum deliberately created in the enormous sphere.

That sends the air roaring down the tunnel at up to 18 times the speed of sound — fast enough to traverse more than 30 football fields in the time it takes to blink. Smack in the middle of the tunnel during a test, attached to a pole capable of changing its angle in fractions of a second, is a scale model of the hypersonics prototype. That is, instead of testing the missiles by flying them through the air outdoors, the tunnel effectively makes the air fly past them at the same incredible pace.

Daniel Marren, an aerospace engineer, in front of a high-velocity wind tunnel at the testing facility in White Oak, Md. Dan Winters for The New York Times

For the tests, the models are coated with a paint that absorbs ultraviolet laser light as it warms, marking the spots on their ceramic skin where frictional heat may threaten the structure of the missile; engineers will then need to tweak the designs either to resist that heat or shunt it elsewhere. The aim, Marren explains, is to see what will happen when the missiles plow through the earth's dense atmosphere on their way to their targets.

It's challenging work, replicating the stresses these missiles would endure while whizzing by at 30 times the speed of a civilian airliner, miles above the clouds. Their sleek, synthetic skin expands and deforms and kicks off a plasma like the ionized gas formed by superheated stars, as they smash the air and try to shed all that intense heat. The tests are fleeting, lasting 15 seconds at most, which require the sensors to record their data in thousandths of a nanosecond. That's the best any such test facility can do, according to Marren, and it partly accounts for the difficulty that defense researchers have had in producing hypersonics, even after about $2 billion-worth of federal investment before this year.

Nonetheless, Marren, who has worked at the tunnel since 1984, is optimistic that researchers will be able to deliver a working missile soon. He and his team are operating at full capacity, with hundreds of test runs scheduled this year to measure the ability of various prototype missiles to withstand the punishing friction and heat of such rapid flight. "We have been prepared for this moment for some time, and it's great to lean forward," Marren says. The faster that weapons systems can operate, he adds, the better.

Last year, the nation was confronted with a brief reminder of how Cold War-era nuclear panic played out, after a state employee in Hawaii mistakenly sent out an emergency alert declaring that a "ballistic missile threat" was "inbound." The message didn't specify what kind of missile — and, in fact, the United States Army Space and Missile Defense Command at two sites in Alaska and California may have some capability to shoot down a few incoming ballistic missiles — but panicked Hawaii residents didn't feel protected. They reacted by careening cars into one another on highways, pushing their children into storm drains for protection and phoning their loved ones to say goodbye — until a second message, 38 minutes later, acknowledged it was an error.

Hypersonics pose a different threat from ballistic missiles, according to those who have studied and worked on them, because they could be maneuvered in ways that confound existing methods of defense and detection. Not to mention, unlike most ballistic missiles, they would arrive in under 15 minutes — less time than anyone in Hawaii or elsewhere would need to meaningfully react.

How fast is that, really? An object moving through the air produces an audible shock wave — a sonic boom — when it reaches about 760 miles per hour. This speed of sound is also called Mach 1, after the Austrian physicist Ernst Mach. When a projectile flies faster than Mach's number, it travels at supersonic speed — a speed faster than sound. Mach 2 is twice the speed of sound; Mach 3 is three times the speed of sound, and so on. When a projectile reaches a speed faster than Mach 5, it's said to travel at hypersonic speed.

One of the two main hypersonic prototypes now under development in the United States is meant to fly at speeds between Mach 15 and Mach 20, or more than 11,400 miles per hour. This means that when fired by the U.S. submarines or bombers stationed at Guam, they could in theory hit China's important inland missile bases, like Delingha, in less than 15 minutes. President Vladimir Putin has likewise claimed that one of Russia's new hypersonic missiles will travel at Mach 10, while the other will travel at Mach 20. If true, that would mean a Russian aircraft or ship firing one of them near Bermuda could strike the Pentagon, some 800 miles away, in five minutes. China, meanwhile, has flight-tested its own hypersonic missiles at speeds fast enough to reach Guam from the Chinese coastline within minutes.

One concept now being pursued by the Defense Advanced Research Projects Agency uses a conventional missile launched from air platforms to loft a smaller, hypersonic glider on its journey, even before the missile reaches its apex. The glider then flies unpowered toward its target. The deadly projectile might ricochet downward, nose tilted up, on layers of atmosphere — the mesosphere, then the stratosphere and troposphere — like an oblate stone on water, in smaller and shallower skips, or it might be directed to pass smoothly through these layers. In either instance, the friction of the lower atmosphere would finally slow it enough to allow a steering system to maneuver it precisely toward its target. The weapon, known as Tactical Boost Glide, is scheduled to be dropped from military planes during testing next year.

Under an alternative approach, a hypersonic missile would fly mostly horizontally under the power of a "scramjet," a highly advanced, fanless engine that uses shock waves created by its speed to compress incoming air in a short funnel and ignite it while passing by (in roughly one two-thousandths of a second, according to some accounts). With its skin heated by friction to as much as 5,400 degrees, its engine walls would be protected from burning up by routing the fuel through them, an idea pioneered by the German designers of the V-2 rocket.

The unusual trajectories of these missiles would allow them to approach their targets at roughly 12 to 50 miles above the earth's surface. That's below the altitude at which ballistic missile interceptors — such as the costly American Aegis ship-based system and the Thaad ground-based system — are now designed to typically operate, yet above the altitude that simpler air defense missiles, like the Patriot system, can reach.

Officials will have trouble even knowing where a strike would land. Although the missiles' launch would probably be picked up by infrared-sensing satellites in its first few moments of flight, Griffin says they would be roughly 10 to 20 times harder to detect than incoming ballistic missiles as they near their targets. They would zoom along in the defensive void, maneuvering unpredictably, and then, in just a few final seconds of blindingly fast, mile-per-second flight, dive and strike a target such as an aircraft carrier from an altitude of 100,000 feet.

During their flight, the perimeter of their potential landing zone could be about as big as Rhode Island. Officials might sound a general alarm, but they'd be clueless about exactly where the missiles were headed. "We don't have any defense that could deny the employment of such a weapon against us," Gen. John E. Hyten, commander of United States Strategic Command, told the Senate Armed Services Committee in March 2018. The Pentagon is just now studying what a hypersonic attack might look like and imagining how a defensive system might be created; it has no architecture for it, and no firm sense of the costs.

Developing these new weapons hasn't been easy. A 2012 test was terminated when the skin peeled off a hypersonic prototype, and another self-destructed when it lost control. A third hypersonic test vehicle was deliberately destroyed when its boosting missile failed in 2014. Officials at Darpa acknowledge they are still struggling with the composite ceramics they need to protect the missiles' electronics from intense heating; the Pentagon decided last July to ladle an extra $34.5 million into this effort this year.

The task of conducting realistic flight tests also poses a challenge. The military's principal land-based site for open-air prototype flights — a 3,200-square-mile site stretching across multiple counties in New Mexico — isn't big enough to accommodate hypersonic weapons. So fresh testing corridors are being negotiated in Utah that will require a new regional political agreement about the noise of trailing sonic booms. Scientists still aren't sure how to accumulate all the data they need, given the speed of the flights. The open-air flight tests can cost up to $100 million.

The most recent open-air hypersonic-weapon test was completed by the Army and the Navy in October 2017, using a 36,000-pound missile to launch a glider from a rocky beach on the western shores of Kauai, Hawaii, toward Kwajalein Atoll, 2,300 miles to the southwest. The 9 p.m. flight created a trailing sonic boom over the Pacific, which topped out at an estimated 175 decibels, well above the threshold of causing physical pain. The effort cost $160 million, or 6 percent of the total hypersonics budget proposed for 2020.

In March 2018, Vladimir Putin, in the first of several speeches designed to rekindle American anxieties about a foreign missile threat, boasted that Russia had two operational hypersonic weapons: the Kinzhal, a fast, air-launched missile capable of striking targets up to 1,200 miles away; and the Avangard, designed to be attached to a new Sarmat intercontinental ballistic missile before maneuvering toward its targets. Russian media have claimed that nuclear warheads for the weapons are already being produced and that the Sarmat missile itself has been flight-tested roughly 3,000 miles across Siberia. (Russia has also said it is working on a third hypersonic missile system, designed to be launched from submarines.) American experts aren't buying all of Putin's claims. "Their test record is more like ours," said an engineer working on the American program. "It's had a small number of flight-test successes." But Pentagon officials are convinced that Moscow's weapons will soon be a real threat.

The exterior of the wind tunnel. At 40 feet long and five feet in diameter, the tunnel replicates the forces missiles would endure at hypersonic speeds. Dan Winters for The New York Times

Analysts say the Chinese are even further along than the Russians, partly because Beijing has sought to create hypersonic missiles with shorter ranges that don't have to endure high temperatures as long. Many of their tests have involved a glide vehicle. Last August, a contractor for the Chinese space program claimed that it successfully flight-tested a gliding hypersonic missile for slightly more than six minutes. It supposedly reached a speed exceeding Mach 5 before landing in its target zone. Other Chinese hypersonic missile tests have reached speeds almost twice as fast.

And it's not just Russia, China and the United States that are interested in fast-flying military power drills. France and India have active hypersonics development programs, and each is working in partnership with Russia, according to a 2017 report by the Rand Corp., a nonpartisan research organization. Australia, Japan and the European Union have either civilian or military hypersonics research underway, the report said, partly because they are still tantalized by the prospect of making super-speedy airplanes large enough to carry passengers across the globe in mere hours. But Japan's immediate effort is aimed at making a weapon that will be ready for testing by 2025.

This is not the first time the United States or others have ignored risks while rushing toward a new, apparently magical solution to a military threat or shortcoming. During the Cold War, America and Russia competed fiercely to threaten each other's vital assets with bombers that took hours to cross oceans and with ballistic missiles that could reach their targets in 30 minutes. Ultimately, each side accumulated more than 31,000 warheads (even though the detonations of just 100 weapons would have sparked a severe global famine and stripped away significant protections against ultraviolet radiation). Eventually the fever broke, partly because of the Soviet Union's dissolution, and the two nations reduced their arsenals through negotiations to about 6,500 nuclear warheads apiece.

Since then, cycles of intense arms racing have restarted whenever one side has felt acutely disadvantaged or spied a potential exit from what the political scientist Robert Jervis once described as the "overwhelming nature" of nuclear destruction, a circumstance that we've been involuntarily and resentfully hostage to for the past 70 years.

[*Putin Warns That Russia Is Developing 'Invincible' Hypersonic Missiles*]

Trump officials in particular have resisted policies that support Mutual Assured Destruction, the idea that shared risk can lead to stability and peace. John Bolton, the national security adviser, was a key architect in 2002 of America's withdrawal from the Anti-Ballistic Missile Treaty with Russia, which limited both nations' ability to try to block ballistic missiles. He asserted that freeing the United States of those restrictions would enhance American security, and if the rest of the world was static, his prediction might have come true. But Russia started its hypersonics program to ensure it could get around any American ballistic missile defenses. "Nobody wanted to listen to us" about the strategic dangers of abandoning the treaty, Putin said last year with an aggressive flourish as he displayed videos and animations of his nation's hypersonic missiles. "So listen now."

But not much listening is going on in either country. In January, the Trump administration released an updated missile-defense strategy that explicitly calls for limiting mutual vulnerability by defeating enemy "offensive missiles prior to launch." The administration also continues to eschew any new limits on its own missiles, arguing that past agreements lulled America into a dangerous post-Cold War "holiday," as a senior State Department official described it.

The current administration's lack of interest in regulating hypersonics isn't that different from its predecessor's. Around 2010, President Obama privately "made it clear that he wanted better options to hold North Korean missiles" at risk, a former senior adviser said, and some military officials said hypersonic weapons might be suitable for this. About that same time, the most recent nuclear arms reduction agreement with Russia deliberately excluded any constraints on hypersonic weapons. Then, three years ago, a New York-based group called the Lawyers Committee on Nuclear Policy, acting in conjunction with other nonprofits committed to disarmament, called on the president to head off a hypersonic competition and its anticipated drain on future federal budgets by exploring a joint moratorium with China and Russia on testing. The idea was never taken up.

The Obama administration's inaction helped open the door to the 21st-century hypersonic contest America finds itself in today. "We always do these things in isolation, without thinking about what it means for the big powers — for Russia and China — who are batshit paranoid" about a potential quick, pre-emptive American attack, the adviser said, expressing regret about how the issue was handled during Obama's tenure.

While it might not be too late to change course, history shows that stopping an arms race is much harder than igniting one. And Washington at the moment is still principally focused on "putting a weapon on a target," as a longtime congressional staff member put it, rather than the reaction this capability inspires in an adversary.

Griffin even projects an eventual American victory in this race: In April 2018, he said the best answer to the Chinese and Russian hypersonic programs is “to hold their assets at risk with systems similar to but better than what they have fielded.” Invoking the mantra of military scientists throughout time, Griffin added that the country must “see their hand and raise them one.” The world will soon find out what happens now that the military superpowers have decided to go all in.