Statement of

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Examining R&D Pathways to Sustainable Aviation

Executive Summary

Chairman Beyer, Ranking Member Babin and distinguished members of the Subcommittee, thank you for the opportunity to testify. My name is Dr. Karen Thole and I hold the title of Distinguished Professor and Department Head of Mechanical Engineering at the Pennsylvania State University. My expertise is in gas turbine heat transfer in which I have researched innovative cooling technologies that have gone from theory to application. My research laboratories have been given the distinction of being Centers of Excellence in aerodynamics and heat transfer for two gas turbine manufacturers. The opinions expressed in my testimony today are that of my own and do not represent views of the Pennsylvania State University.

Commercial aviation is responsible for between 2.0 and 2.5 percent of the total global CO_2 emissions of which 90 percent comes from large single-aisle and twin-aisle aircraft. In response to a request from the National Aeronautics and Space Administration (NASA), the National Academies of Sciences, Engineering, and Medicine (NASEM) convened a committee in 2015 to develop a national research agenda for reducing CO_2 emissions from commercial aviation [1]. In 2016, the National Academies published the committee's report, which led the Chief Technology Officers of seven of the world's major aviation manufacturers to jointly sign an agreement on a unified commitment to reduce commercial aviation emissions by half in 2050 relative to levels in 2005 [2]. This briefing provides a summary and an update on the four research approaches that were recommended by the 2016 National Academies report for sustainable aviation: (1) advances in aircraft-propulsion integration; (2) improvements in gas turbine engines; (3) development of turboelectric propulsion systems; and (4) advances in sustainable alternative jet fuels. I co-chaired the National Academies committee with some of my remarks below taken from the 2016 National Academies report.

It is my opinion that sustainable alternative jet fuels are a viable direction to provide a near- and mid-term reduction in CO_2 emissions. Despite the ongoing discussions related to hydrogen as an aviation fuel, there are significant technoeconomic and safety concerns identified in the 2016 National Academies report that did not make hydrogen a viable solution within the 2050 timeframe. Last

November, however, the Department of Energy released their Hydrogen Program Plan that provides a framework and coordinated effort for a hydrogen transition in the United States. Also, late last year, Airbus announced that they are developing a new zero-emission blended wing aircraft concept powered by two hybrid turbofan engines that will use hydrogen. Unlike the European Union, which has an aggressive hydrogen-powered aviation plan, the U.S. is missing a long-term strategy for using hydrogen in the aviation sector to reduce CO_2 emissions.

In agreement with the 2016 study, I believe we need to invest in new aircraft architectures that take full advantage of the potential benefits of turboelectrics and of hybrid electric propulsion systems. Key to both turboelectrics and hybrid electric systems are continued improvements needed in propulsive and thermal efficiencies, especially for small core gas turbines. Many propulsive and thermal efficiency improvements can also be directly applied to conventional gas turbines which is synergistic with meeting the needs for military propulsion. These improvements in efficiency can happen by using all of our available new tools such as advanced manufacturing and materials, machine learning, and sensor technologies.

In my opinion, provided there is strong research and development support, we are likely to see a range of innovative solutions emerge for creating sustainable aviation starting with the use of sustainable alternative jet fuels progressing towards hybrid electric propulsion followed by the use of hydrogen either for fuel cells or for producing synthetic fuels. It is obvious that we are racing with China and the European Union to develop these solutions because of the climate as well as economic benefits. Heavy investments are needed now to support ongoing research efforts and the education of a new workforce equipped with the latest technological tools to advance the U.S. aviation industry so that it will be sustainable and competitive.

Overview of Carbon Emissions Resulting from Aviation

Commercial aviation, like every means of mass transportation, releases carbon dioxide (CO_2) into the atmosphere. Relative to other means of mass transportation, however, commercial aviation is the most challenging because of technical, economic, and policy changes required not only for new technologies and infrastructure but also because of the high safety standards that are implemented in this industry.

The primary human activities that release carbon dioxide (CO_2) into the atmosphere are the combustion of fossil fuels (coal, natural gas, and oil) to generate electricity, the provision of energy for transportation, and as a consequence of some industrial processes. Although aviation CO_2 emissions only make up approximately 2.0 to 2.5 percent of total global annual CO_2 emissions, research to reduce CO_2 emissions is urgent because new technology requires a long time to propagate into and through the aviation fleet; because of the ongoing impact of global CO_2 emissions; and because of the international race to develop new products to meet increasingly stringent safety requirements.

Typical passenger capacity for different aircraft range between general aviation with fewer than 6 passengers to large aircraft including single-aisle with more than 100 passengers and twin-aisle with more than 200 passengers. Within these classes of aircraft, 90 percent of the CO_2 emissions from global commercial aircraft are generated by large aircraft (single- and twin-aisle). Therefore, any technologies for reducing the carbon emission from commercial aircraft will need to be applicable to and effective at this scale aircraft and must be widely deployed.

CO_2 emissions from a commercial aircraft can be reduced in the following ways:

- Reduce the energy required to fly by the aircraft by reducing its weight and/or drag;
- Improve the efficiency with which the energy is converted from fuel into thrust;
- Reduce the carbon intensity of the energy required—in other words, reduce the net amount of carbon that is emitted into the atmosphere to generate a given amount of energy.

In response to National Aeronautics and Space Administration (NASA), the National Academies of Sciences, Engineering, and Medicine convened a committee in 2015 to develop a national research agenda for reducing CO_2 emissions from commercial aviation [1]. To simplify the writing throughout the remainder of the paper, I will refer to this report as the 2016 National Academies report. Four high priority research approaches were identified to develop propulsion and energy system technologies that could reduce CO_2 emissions from global civil aviation and that could be introduced into service during the next 10 to 30 years:

- Advances in aircraft-propulsion integration;
- Improvements in gas turbine engines;
- Development of turboelectric propulsion systems; and
- Advances in sustainable alternative jet fuels.

For each of these approaches, several specific research projects were recommended by the committee. Considerations were given for each as to the breadth of applicability, ease of integration, technical and economic risks, and impact. The breadth of applicability, for instance, was compared between drop-in sustainable fuels that are applicable to all current and future jet aircraft, while improved technologies for fully electrical propulsion systems are more applicable only to future generations of small aircraft. During the study committee's work, significant discussions were given to the all-electric and hybrid-electric propulsion systems, particularly because these concepts have already been demonstrated and are even flying for small general-aviation aircraft. However, significant challenges exist in directly scaling these concepts to meet the demands of large aircraft given their sizes and long flight distances. Alternatively, the committee strongly recommended the development of turboelectric systems, which differ from the all-electric and hybrid concepts because no additional batteries or fuel cells are required. Turboelectric propulsion systems require high power generators, cabling, and power electronics, and like other electric propulsion systems they make beneficial concepts such as distributed propulsion much more feasible. In 2021, gas turbine manufacturers are actively evaluating all of these designs including the benefits for a family of parallel hybrid architectures that do require large, advanced batteries. Development and demonstration of these technologies in concert with NASA will accelerate their deployment.

In response to the findings of the 2016 National Academies report, the Chief Technology Officers of seven of the world's major aviation manufacturers jointly signed an agreement on a unified commitment titled, "The Sustainability of Aviation" at the 2019 Paris Airshow [2]. Through the Air Transport Action Group, the aviation industry set an ambitious target to reduce CO_2 emissions by 2050 to half of the levels that occurred in 2005. Prior to the COVID-19 pandemic, the emissions of CO_2 were rising by approximately 1% per year over the previous decade with no growth in 2019 [3]. The governmental policies during the COVID-19 pandemic drastically altered the energy demand around the world, particularly commercial aviation. The daily global CO_2 emissions decreased by 17% by early April 2020 compared with 2019 levels [3].

The strategy outlined in The Sustainability of Aviation agreement included three strategies, which are similar to those proposed by the 2016 National Academies report:

- Continue to develop aircraft and engine design and technology;
- Support the commercialization of sustainable, alternate aviation fuels; and
- Develop radically new aircraft and propulsion technology to enable a new generation of aviation.

In recent times the use of liquid hydrogen (H_2) as an aviation fuel has gained international attention. With three times the energy density of kerosene, H_2 promises not just net carbon neutrality, but zero CO_2 emissions. The potential exists for H_2 to be generated in the gaseous state using green electricity produced from renewable energy sources such as solar, wind, geothermal, biogas, nuclear, and other hydroelectric sources unlike now where most H_2 is produced from fossil fuels such as coal and natural gas using processes that release CO_2 into the atmosphere. In considering ease of integration into commercial aviation, the impact on aircraft design and performance, and additional and economic considerations, the case for making use of H_2 as a fuel source for large aircraft is difficult to defend. Added to these challenges are the nearly insurmountable safety challenges. The 2016 National Academies committee assessed the viability and decided not to classify hydrogen fuel technologies as a high priority. Nonetheless, the development of a national research plan and modest support for this technology remains appropriate to ensure the U.S. global leadership in aerospace propulsion.

Through the remainder of this document, the needed research approaches suggested by the 2016 National Academies report along with The Sustainability of Aviation agreement will be discussed along with the potential of using liquid hydrogen (H_2) as an aviation fuel. After the required research is described, additional information is provided on the international competition and workforce needs for the aviation industry.

Research Priorities Required for Sustainable Aviation

Advances in Aircraft-Propulsion Integration. Two high-priority research projects were identified in the 2016 National Academies report for integration that requires a design disruption beyond discrete improvements to individual component technologies. Research is needed to make both evolutionary improvements in reducing the fan pressure ratio in nacelles and to make revolutionary improvements beyond the traditional tube-and-wing platform that would enable distributed propulsion concepts and boundary layer ingestion configurations. Unducted fans avoid weight and drag penalties, but the inability to contain airfoil components and high noise levels result in the majority of aircraft being powered by turbofans with ducted fans. In turbofans, the fan is placed in a duct (nacelle) where improvements in propulsive efficiency can be gained by reducing the fan pressure ratio because it lowers the fan's exhaust velocity. Reducing the fan pressure ratio can be accomplished by increasing the fan diameter, decreasing the core of the gas turbine engine inside the duct, or using distributed propulsion. These solutions require a change in the airframe configuration since we have already exhausted the maximum nacelle size because of the constraints of mounting ~~of~~ the engine to the wings with respect to the landing gear heights on existing airframe architectures. An optimal balance is needed between these solutions with that of the additional weight and drag induced. Other possible integration systems exist, including embedding the engine within the wings.

The specific high priority research projects for this approach were as follows: (1) develop nacelle and integration technologies to enable ultrahigh bypass ratio propulsors and (2) enable concepts that allow the ingestion of the boundary layer that develops on the aircraft body such that the velocity defect in the aircraft wake will be reduced. By reducing the velocity defect through boundary layer ingestion, the required thrust is reduced and thereby the amount of energy consumed is also reduced. It is my opinion that these research issues are unanswered and that the timeframe to conduct relevant research and testing in this area requires that we provide a concerted level of funding now to advance airframe architectures beyond tube-and-wing designs.

Improvements in gas turbine engines. Turbine engines are the devices that convert the energy in fuel into shaft power, which is then converted to propulsive power. The commercial and military aircraft designed in the last 40 years are primarily powered by gas turbine engines, either turbofans or turboprops. It is also important to note that gas turbines meet 40% of the U.S. demand for electricity and that many of the technologies developed for aviation applications can directly be used to make electrical power generation more sustainable. There are some notable differences, however, between the two applications including weight and volume limitations being only relevant to aviation and a wider variety of fuel types, for example H_2, being only relevant to power generation.

With the exception of fully electric, even the majority of the hybrid propulsion and turboelectrics aviation propulsion systems use a gas turbine as the power plant. Given this need, the 2016 National Academies report stated it is imperative that if we are to reduce our CO_2 emissions, significant research attention is needed for improving the overall efficiency of gas turbine engines, which is the product of the propulsive efficiency (conversion of shaft power to propulsive power) and motor thermodynamic efficiency (conversion of fuel flow power to shaft power), which is often referred to as thermal efficiency. Today's aircraft operate with propulsive efficiencies of up to 70 percent and thermal efficiencies of up to 55 percent, both of which have steadily improved over many decades given innovations, significant testing, and improved design tools. Of note is that an aircraft in flight produces 15 percent fewer grams of CO_2 per kilowatt-hour than that of the world's electric grid. To achieve these efficiencies, today's turbine engines operate at temperatures much above the melting temperatures of the turbine components through the use of highly advanced cooling technologies. It is not clear as to the theoretical limits of what can be achieved in terms of increases in efficiencies from a practical consideration; however, the 2016 National Academies report estimates that further improvements of up to 70 percent for the thermal efficiency and of 90-95 percent for propulsive efficiency may be achievable. The report defines a number of research projects to move towards these goals.

Not discussed in the 2016 National Academies report is an important illustration as to the impact of innovation that increases overall efficiencies. In 2016, Pratt & Whitney introduced a Geared Turbofan (GTF), for which the company has already received 10,000 new engine orders. The GTF operates by de-coupling the fan from the turbine, thereby allowing each to operate with optimal performance. The disruptive technology introduced by the GTF has led to a reduction of about 100 gallons in aviation fuel for every flight hour relative to legacy engines [4]. In turn, this reduction in fuel leads to CO_2 savings of about 3600 metric ton per year per aircraft, which equates to removing 800 cars from the road for one year or removing 2,000 cars from the road for the life of the aircraft. Technology disruptions are also illustrated by CFM International (a joint venture between Safran Aircraft Engines and GE Aircraft) in which it launched an engine program in 2008 called LEAP-X. The LEAP-X makes use of advanced aerodynamics and new material technologies including ceramic matrix composites, which enable higher temperatures. The LEAP-X has also taken advantage of advanced manufacturing, particularly 3D metal printing, which has enabled a new fuel nozzle design. In 2019, LEAP production rose to 1,736 engines with orders and commitments reaching 1,968 even amid the 737 MAX grounding, and there is a stable backlog of 15,614 engines [5].

During the power extraction in the turbine section of a gas turbine, the blades spin at tens of thousands of revolutions per minute while experiencing gas flow temperatures exceeding their melting temperatures. The stresses experienced by the spinning blades can be equated to hanging approximately five sports cars from a single blade. Current convention is to manufacture these blades by growing single crystal alloys, which is an art that fewer countries can do than the number of countries that can make nuclear weapons. The ability to cast turbine blades is a competitive advantage that the U.S. retains, but this process comes with manufacturing times on the order 90 weeks at a cost of over one million dollars to cast a set of developmental test blades. Metal 3D printing technology is being embraced by turbine manufacturers, particularly for turbine development, and in some cases for the production of static parts such as the LEAP-X fuel nozzle. In contrast to the time and costs for conventional methods, a set of development turbine blades made using metal 3D printing can be done in a matter of a few weeks at a cost of less than $30,000. Metal 3D printing, however, is still in its infancy since we need to show similar performance between cast and printed; and we need high temperature materials that can be used for metal 3D printing. One other opportunity that metal 3D printing offers is the ability to embed sensors in turbine components where it may otherwise not have been possible or where it was not possible to retain sensors due to the harsh environments. Integrating sensors, too, is in its infancy but is beginning to emerge. The opportunities of additive and the research priorities for the gas turbine industry were addressed through a second National Academies study completed in 2020 on advances needed for aviation and power generation gas turbines, which was commissioned by the Department of Energy [6]. There is a great deal of synergy between the 2016 and 2020 National Academies reports with regards to the research approaches needed for turbines.

In response to the needs of the aviation community, NASA is working with gas turbine manufacturers through the Hybrid Thermally Efficient Core (HyTEC) Program, which is aimed at achieving a 5 to 10% fuel burn reduction relative to the 2020 best in class, reducing the engine core size to facilitate hybridization, lowering environmental impacts, and reducing end-user costs. They have set forth goals to extract power up to four times that of the current state-of-the-art turbofan engine at altitude and allow more electrified aircraft systems with optimized electric power availability.

The high-priority research projects defined by the 2016 National Academies report for improving gas turbines were all focused on improving efficiency. Research to increase propulsive efficiency should be focused on turbofans since they power the vast majority of the aircraft. This research should seek to reduce the pressure loss of the gas flow as it passes through the fan and, as already mentioned, reducing the fan pressure ratio while taking into account overall system weight and noise. Research to improve the thermal efficiency of gas turbines should focus on the development of materials and coatings that will enable higher engine operating temperatures. This development will make it possible to increase compressor exit and turbine inlet temperatures.

Improved aircraft efficiency means that turbine engine cores will shrink because aircraft will be able to use propulsion systems with less power. High efficiency is harder to achieve, however, given manufacturing constraints and tolerances. The 2016 National Academies report therefore also recommends research to develop technologies to improve the efficiency of engines with small cores. Area of particular interest include turbomachinery aerodynamic performance, manufacturing, thermal management, combustion, and the lifespan of turbine airfoils.

In my opinion all of high-priority research projects identified above are of value. To support research to improve turbomachinery aerodynamic performance, manufacturing, thermal management, combustion, and the lifespan of turbine airfoils, we need advanced development tools that enable trade-off studies between size and efficiency as cores shrink; reduction of cooling and secondary flows that allows higher temperatures; continued emission studies of current combustion systems while shrinking the combustor to reduce weight; actuation and sensors for advanced control strategies; evaluating alternative thermodynamic cycles as compared to today's simple Brayton cycle and concurrently the development of compact, efficient heat exchangers needed for advanced cycles. In addition to the high priority research projects listed in the 2016 National Academies report, emphasis should be placed on developing materials that allow 3D metal printing which reduce time and costs of development as these are critical to the U.S. Research emphasis is needed on also developing the latest high-fidelity simulation tools, machine learning, and 3D printing all of which can support the digital thread.

Electric Propulsion. The study committee evaluated the use of numerous electric propulsion architectures that fell into three primary groupings: all electric; hybrid electric; and turboelectric. The all-electric system uses only batteries while the hybrid systems and turboelectric systems all use gas turbine engines as the power source. The hybrid systems use the gas turbine engines to charge batteries, which also provides energy for propulsion during one or more of the phases of the flights. The turboelectric configurations do not rely on batteries for propulsion energy during any phase of the flight. Rather, they drive electric generators that power the propulsion system. All three architectures are compatible with the use of a distributed propulsion system that uses many, small individual motors instead of just two large engines, as is typical of conventional commercial aircraft.

Given the current and projected performance of characteristics of batteries in 2015 when the National Academies study committee convened, the committee elected not to recommend the all-electric and hybrid electric architectures as high research priorities because of the gap between the specific power requirements needed for large single-aisle and twin-aisle aircraft and what was available or projected to be available for batteries. It was unlikely that either an all-electric or hybrid electric propulsion system could be fully FAA certified during the subsequent 10 to 30 years, which was the timeline for the 2016 National Academies report. Potential applications (and time frames) for all-electric and hybrid concepts were based largely on projected advances in battery energy storage technology. Jet fuel is an excellent way to store energy, with an equivalent specific energy of approximately 13,000 Wh/kg. A regional or single-aisle aircraft is conceivable with batteries having a specific energy of "only" 800 Wh/kg for a hybrid system (or 1,800 Wh/kg for an all-electric system). Even so, these levels far exceed both the current state of the art Lithium ion batteries (200-250 Wh/kg) and the committee's projection of how far the state of the art would advance during the subsequent 20 years (400-600 Wh/kg). Of course, smaller general aviation aircraft designed for short-range missions can and have been designed with less-advanced batteries. In 2021, the specific energy capabilities are still consistent with those given by the 2016 National Academies report.

Turboelectric concepts are not dependent upon energy storage technologies, but to reduce CO_2 emissions these concepts need to take full advantage of the aircraft-propulsion integration using boundary layer ingestion and distributed propulsion as previously described. Turboelectrics, in general, have lower efficiency than conventional gas turbine propulsion because of the particular energy conversion and transmission losses such that the advantages that it offers through boundary layer ingestion and distributed propulsion must outweigh the inefficiencies of the turboelectric architecture.

The recommended research projects include: turboelectric aircraft system studies to establish metrics and the development of megawatt-class research facilities that allow relevant ground-based testing in support of this size class. In response to these needs, NASA developed a test bed, referred to as the NASA Electric Aircraft Testbed (NEAT), to design develop, assemble and test electric aircraft power systems from a small one person aircraft up to 20 MW airliners, which allows ground-based testing of a full-scale electric aircraft powertrain [7]. Ongoing studies are taking place in the NEAT.

Sustainable Alternative Jet Fuels. Drop-in sustainable jet fuels have aggregate properties that are essentially equivalent to those of conventional (petroleum-based) jet fuels and, as such, are fully compatible with existing aircraft and the existing infrastructure such as pipelines and airport fuel systems. Sustainable alternative jet fuels are a family of drop-in fuels intended to lower the net life-cycle carbon emissions of commercial aviation. Jet fuels need to meet current specifications either on their own or when blended with conventional jet fuel such that these are "drop-in" replacements can be directly used as jet fuel with no impacts on performance. Alternative refers to the fact that these are produced primarily from non-petroleum sources of hydrocarbons (particularly agricultural and wood product) using a broad range of biochemical and thermochemical conversion processes. Sustainable refers to the ability to reduce net life-cycle carbon emissions relative to conventional jet fuel and in terms of environmental, societal, and economic factors.

Sustainable alternative jet fuels were endorsed by the 2016 National Academies study as one of the high research priorities and it is my opinion that this particular area is one that is best positioned to providing a near- to mid-term impact in reducing CO_2 emissions. Unlike hydrogen, which will be discussed below, existing aircraft have already been powered by sustainable alternative jet fuels since 2019 for United Airlines flights from Chicago to Los Angeles. United has committed $40M in investments to accelerate the production of sustainable alternative jet fuels, and it has agreed to purchase up to 10 million gallons over the next two years. Delta also entered into an agreement to purchase 10 million gallons per year and set aside $2M for research. Given Dr. Csonka will also testify at this hearing, more details will be provided by him as to the current state of sustainable alternative jet fuels.

Specific research projects recommended by the 2016 National Academies study included: modelling and analyses of the sustainable alternative jet fuel development; feedstock development; conversion processes and scale-up in production; and fuel testing and certification. These are, for the most part, ongoing research projects that are taking place.

Hydrogen as an Energy Source in Aviation. As was mentioned, the 2016 National Academies committee specifically assessed the possibility of using H_2 fuel for aviation propulsion and decided that research in this area was not a high priority for large aircraft that could become operational in the subsequent 10 to 30 years. Today, however, numerous discussions are taking place on the potential of hydrogen for both ground-based power generation (producing electricity) as well as aircraft propulsion.

Almost all of today's hydrogen is produced by natural gas or coal using processes that discharge CO_2 into the atmosphere. Using hydrogen produced in this way as a jet fuel results in no net reduction in atmosphere CO_2. In the future, there is a growing potential for making hydrogen from water using hydrolysis from green electricity to the extent that available green electricity exceeds total electrical demand on a particular power grid. The amount of H_2 that would have been required to meet the 2019 energy needs for jet fuel equates to approximately 14% of the world's electricity, which means that a significant amount of excess electricity would be required to meet the demands for H_2 as an aviation fuel if all were produced using green electricity [9]. To implement this fuel solution, significant infrastructure is required to produce, liquefy gaseous H_2 to the required liquid state for engines, and to distribute the hydrogen to airports through pumping or some other means. Liquefying H_2 costs are projected to be between 30 and 50 percent of the input energy costs. In addition to the infrastructure costs, entire aircraft fleets would need replacing.

In September 2020, Airbus reported that the company is developing a new zero-emission blended wing aircraft concept referred to as ZEROe [10]. A key part of this concept is that it would be powered by two hybrid turbofan engines using hydrogen as their energy source. To implement hydrogen as a fuel, aircraft designs would need to radically change. The fuel tanks need to be highly insulated for the liquid hydrogen to be maintained at -400F and need to be three times larger than existing fuel tanks on today's aircraft [9]. These storage requirements in turn add to the weight and drag of the aircraft which puts into question the overall efficiency that sets the amount of required fuel. Although these concerns are not necessarily insurmountable, the most compelling challenge is one of safety for the passengers who would be surrounded by highly flammable liquid H_2.

In my opinion, overcoming the technoeconomic and safety challenges in using H_2 as an aviation fuel are challenging in the timeframe in which we are looking for solutions to reduce CO_2 emissions (that is, by 2050). There are other opportunities for the aviation sector, however, including the recycling of atmospheric CO_2 into synthetic fuels using renewable energy, which offers an energy concept with no net CO_2 emission. Provided the right investments were made now, the European Union's Clean Sky Program estimates that hydrogen as a fuel source either through fuel cells, combustion in gas turbine engines or as building blocks for synthetic liquid fuels could result in a first short-range hydrogen-powered demonstrator by 2028. It is my opinion, that the U.S. needs to develop a longterm strategy for hydrogen specifically for the aviation sector to remain competitive.

Workforce Challenges and International Competitiveness

The 2016 National Academies report focused on technology. Two related areas of great importance are workforce challenges and international competitiveness.

The U.S. civil aviation industry accounts for more than $1.6 trillion in annual economic activity, supports 10.6 million direct and indirect jobs (contributes 5.1% to GDP), and is one of only a few industry sectors to generate a positive U.S. trade balance—$60 billion in 2019. In 2019, aviation manufacturers directly employed more than 600,000 highly skilled workers, accounting for nearly half of the total aerospace and defense industry workforce [11].

Supporting research in the priority areas already discussed is prudent to reduce CO_2 emissions. Academic institutions, industry, and federal agencies such as NASA, FAA, DOD, and DOE all have a critical role. Academic institutions have historically contributed in advancing technologies to low levels of technology readiness, but today's research at some of the leading universities in which significant financial investments in facilities and personnel have been made provide opportunities to move to higher levels of technology readiness. In the area of gas turbine research, for example, Georgia Tech, Ohio State, Notre Dame, Penn State, Purdue, Texas A&M, and Virginia Tech have made significant investments that have, in turn, resulted in multi-year committed research funding with one or more specific industry partners. These university-industry relationships have led to further research support from federal agencies because of the collaborative efforts and because of the technology transfer that has led to direct impacts on the products. It is my opinion that these partnerships must continue to be supported by the federal government because the investments being made ensure technology transfer and a pipeline of talented employees.

Now more than ever, however, the aviation industry requires a highly educated, diverse, and talented workforce who are not only knowledgeable in the fundamental, traditional areas such as turbomachinery, combustion, gas turbines, airplane design, and controls but equally as knowledgeable on how to use emerging technologies such as, for example, design for additive manufacturing, machine learning, hybrid propulsion systems, high-fidelity computational simulations, and sensor development. The students being educated today need to understand how to apply these tools in order to advance the industry, which can also positively impact our military propulsion capabilities. A lack of diversity in aviation is also holding back our abilities to achieve our goals because diverse thought leads to better solutions. As was mentioned, numerous universities have invested in facilities where students are educated through critical hands-on experiences that will make them successful aviation engineers in the aviation field; however, there are many more universities in which talented students are not being exposed to the opportunities that aviation provides. In addition, many subjects related to aviation require multiple years of study to master. Research support for graduate students from federal agencies as well as industry, which is generally provided one year at a time, often falls short on continued student support to allow that student to master these interdisciplinary subjects. These are the reasons that it is important that the federal government increase the support for dedicated graduate fellowships directed towards aviation, which can be done by expanding the existing fellowship programs offered by NASA and by DOD, for example.

In 2017, the total U.S. spending on research and development totaled $549B, while China came in at $496B. Together, these account for nearly half of the world's global research and development [12]. The rapid growth of China's committed efforts to research funding is clearly indicated in the growing number of patent families (unduplicated measure of global inventions) granted to inventors, of which over half were awarded to China, while the U.S. had only 6.8%. China is also demonstrating rapid growth in the number of paper submissions to academic journals. In 2000, China published only 5% of all papers while the U.S. published 28%. In contrast in 2018, China published 21% of all papers which was higher than the 17% of papers published by the U.S. In 2015, the number of university degrees awarded by China in science and engineering was 2.2 times higher than the U.S. It is no secret that China's research and development strategy is to become the world's leader in science and technology by 2050, which was announced by the "Made in China 2025" plan in 2015 [13]. And, in China's plan, the aviation market is prominently placed. It is for these reasons that as a professor, I have been approached on multiple occasions by Chinese faculty indicating that if I were to collaborate with them in gas turbine heat transfer on joint research programs, an "open spigot of money" would be made available. I have declined such opportunities because I am fortunate to have outstanding support from my industry collaborators and the federal government, but for faculty who want to work in this area and are not so fortunate, China is a viable source of support.

The Clean Sky program funded by the European Union clearly communicates their plan to develop hydrogen as an energy source, which they believe will be disruptive to the industry [14]. Their recent study indicated that hydrogen as a primary energy source for propulsion, either for fuel cells or direct combustion in gas turbines or as a building block for synthetic liquid fuels could power aircraft with entry into service by 2035 for short range aircraft reducing the climate impact by 50 to 90 percent.

It is important to mention that over the last 15 years, there is only one federal program that has provided continual support of research in gas turbines, mostly directed for power generation, and that program is DOE's Advanced Turbines Program including the University Turbine Systems Research Program. Since 2017, NASA has begun offering multi-year research grants through its University Leadership Initiative to support university research in aviation and aeronautics. In both cases, these programs emphasize the close collaboration with industry, and in both cases, they do not have sufficient funds to support the development of many innovations which could otherwise be achieved through greater investments in research. The FAA ASCENT Program has also been critical to funding university research projects at 16 U.S. universities specifically targeted at aviation sustainability.

To remain competitive, it is imperative that the U.S. invests heavily now because of the need for a new cadre of students equipped with new tools to fill the workforce needs and because of the race to develop the best products and solutions for making aviation sustainable.

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[13] https://knowledge4policy.ec.europa.eu/foresight/topic/expanding-influence-east-south/industry-science-innovation_en

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Biographical Sketch

Dr. Karen A. Thole is a Distinguished Professor and head of the Department of Mechanical Engineering at The Pennsylvania State University. Dr. Thole is an ASME Fellow and an AIAA Fellow. She is internationally recognized as a leader in gas turbine heat transfer. Her research has taken innovative cooling technologies from theory to application, which has allowed increases in turbine thermal efficiencies. Dr. Thole has established two research laboratories at Penn State with the most recent housing a unique one stage test turbine. Both laboratories have been awarded the distinction of being Centers of Excellence in aerodynamics and heat transfer for two different gas turbine manufacturers. Dr. Thole has been recognized for her technical contributions by numerous best paper awards, the ASME George Washington Medal and the AIAA Air Breathing Propulsion Award. She has also been recognized for her work in mechanical engineering education and diversity including being selected as a U.S. White House *Champion of Change,* by ASME's Edwin F. Church Medal and by ABET's Claire L. Felbinger Diversity Award. She holds two degrees in Mechanical Engineering from the University of Illinois, and a PhD from the University of Texas at Austin.