# The Broad Economic Impact of Material Science Advancements on fields such as Tribology and Particle Technology

**WRITTEN SUBMISSION**

Testimony before the Subcommittees on Energy and the Subcommittee on Research and Technology,

of the Committee on Science, Space, and Technology,

United States House of Representatives

June 28, 2017

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I appreciate the opportunity to provide this written testimony to the Committee. I am the John & Ann Doerr Professor of Mechanical Engineering, and the Faculty Director of the Rice Center for Engineering Leadership at Rice University in Houston, Texas.

Material science has had a broad impact on our nation, requiring substantial investments in basic science to catapult forward the promise of engineering and science fields such as mine own, Tribology and Particle Technology.

I have over 100 research publications, almost all of them in the areas of Tribology, the study of materials in sliding contact and the associated friction, lubrication, and wear. Tribology comes from a Greek word meaning "to rub" and this gives you a picture of what Tribologists do. Within the field of Tribology, which is largely a field advanced by material scientists, physicists, and mechanical engineers like me, I study problems where surfaces are rubbing against each other and particles are present. This means that I also have expertise in particle technologies, such as those found in the multi-billion dollar solids processing industries. I have numerous pending and provisional patents and my research has been sponsored by federal agencies and departments such as the National Science Foundation (NSF) and the Department of Energy (DOE), and industry, private foundation, and venture-capital entities. I am passionate about mentoring the next-generation of engineering and technology researchers, having advised 100 undergraduate, 30 Masters, 14 doctoral, and 5 postdoctoral research students over the last 13 years. Some of my research has been translated to industry, in the form of computer modeling approaches, and in high-tech start-up activity, such as InnovAlgae, a university research spin-off company I co-founded, that develops advanced algae-related production technologies for the energy and consumer health industries.

There are three topics relevant to my testimony today:

1. New materials can improve the safety and environmental impact of energy production technologies
2. Material advancements can provide the foundation for new technologies in medicine, transportation, manufacturing and computing.
3. The merits of (i) science prize competitions, (ii) university-federal lab/agency partnerships, and (iii) university-company partnerships, in speeding the development of advanced materials.

A final recommendation for supporting basic science research can be found at the end of this document.

**New materials can improve the safety and environmental impact of energy production technologies.**

***Mining and Drilling: energy resource extraction processes*. Mining** operations for energy resources such as coal, in addition to **drilling** for resources such as natural gas can both benefit from advanced coatings. Not only can lubrication-friendly coatings promote energy efficiency in these sectors which expend a lot of energy, wear-resistant coatings can extend lifetimes of drill bits and mining components, thereby accelerating extraction time. In the drilling industry, 'time is money' to the levels of hundreds of thousands of dollars per day so the economic impact can be positively affected if the drilling times are shortened. The development of effective, environmentally friendly additives in drilling muds, may enable more efficient cooling, lubrication, and rock cuttings removal from the drill bit/rock interface. More efficient and environmentally safe extraction processes allow workers to have less exposure time to dangerous activities and likely ensure there are less disturbances to the environment.

***Material advancements can also move forward technology that reduces the impact that fossil fuel energy production processes*.** Material advancements can reduce the impact that energy production processes such as coal and natural gas combustion have on our environment. For example, chemical looping is a thermal particle combustion process that allows you to efficiently separate the carbon dioxide $CO_2$ generated from coal combustion into a pure stream that can be easily taken from a power station's flue gas and captured for long-term storage. A key part of this process being as environmentally safe as possible is the development of innovative metal oxide materials[1] to serve as the oxygen carrying solid particles. For example, nickel (Ni) based oxygen carriers are highly effective in chemical looping yet they are expensive and somewhat toxic. Thus, basic science is needed to find viable non-Ni alternatives to move the technology forward. The upside is that a successful chemical looping process could serve as a viable carbon capture and storage technology, helping America to better enjoy the spoils of its vast natural gas finds without it automatically being detrimental to the environment. My point is not to advocate for this technology, but to show that material advancements, which come from basic science, can make powerful technologies with non-favorable environmental impact, more favorable. The NSF is funding projects on chemical looping and such basic science research can end up producing win-win technology and economic scenarios for our country where the environmental impacts of fossil fuels are lessened.

**Material advancements can provide the foundation for new technologies in medicine, transportation, manufacturing and computing.**

***The technological benefits of material advancements in orthopedic medicine.*** Many Americans have artificial joint implants for their hips or knees. For example, about 250,000 older people age 65 and older are hospitalized for hip fractures each year[2], and almost 95% of these are caused by major falls. By 2030

[1]**Source***: Jing, D., Mattisson, T., Ryden, M., Hallberg, P., Hedayati, A., Van Noyen, J., & Lyngfelt, A. (2013). Innovative oxygen carrier materials for chemical-looping combustion. Energy Procedia, 37, 645-653.*

[2] Centers for Disease Control. National Center for Health Statistics. Health Data Interactive. [Oct. 2015].

alone, the number of hip replacement surgeries in America is expected to explode to 572,000 annually[3]. If you were like my father, who got an artificial knee just a few years ago in his 70s, the surgeon might have told you to wait as long as possible because the implants may only last for 10-15 years. This is because human joints such as knees and hips are synovial joints which means they rub together and have lubricants, similar to mechanical bearings. Unlike the healthy, natural joint, artificial joints are often in partial contact when they are rubbing together. Therefore, these joints wear out and have finite lifetimes so orthopedic surgeons often push their patients to wait as long as possible or until the pain becomes unbearable before getting replacement joints which have finite lifetimes due to the wear and tear.

However, novel materials such as diamond-like carbon (DLC) and nanocrystalline diamond[4] (NCD) may lead to long-lasting artificial joint implants due to their ability to provide the ultimate wear-resistant coating. Advanced coatings such as NCD are not only very smooth when deposited on orthopedic materials, they are hard like diamond, chemically inert (i.e., non-reactive) and compatible with the human body. This type of advance could lead to fewer patients enduring long-term pain (which lessens the need for costly, addictive pain medications) and allows joint replacement surgeries to occur earlier in life – perhaps even before Medicare coverage begins.

***The technological benefits of material advancements in transportation***. New material technologies will also help advance American transportation. A report[5] commissioned by ARPA-E in 2017 and led by researchers from the University of Pennsylvania in concert with other researchers from government and academia outlined some basic opportunities for materials to advance the transportation sector beyond just finding lighter materials. For example, the tires in automobiles and trucks are both blessings and curses. The tires need to grip the road through robust traction performance, and they should also have long lifetime before they wear out. The rolling resistance from today's tires consume a lot of energy in the form of fuel. In other words, it takes more energy to push your child on a bike with tires than to push them on ice skates. However, ice skates do not brake as well as rubber tires. Thus, the goal is to find better tire material which can both roll and brake easily. Material advances such as nanomaterials, which currently are at Technology Readiness Levels[6] (TRL) as low as 2, could soon make their way from the basic science lab to the applied science lab or commercial company's demonstration floor. Tire rolling resistance and high traction compete to hinder fuel performance, but the problem was alleviated somewhat in the 1990s when silica as a reinforcing nanofiller improved performance. Today, thanks to basic science discovery, we have a much better understanding of nanomaterials. With the appropriate level of funding, it is just a matter of time before material discovery leads to an even better tire technology. And the potential gains are enormous, since these proposed new tires have been estimated to save American up to 0.2 quads per year (i.e., 35 million barrels of oil equivalent per year or 0.2 quadrillion Btu, which equals $0.21 \times 10^{18}$J).

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[3] Stryker Corporation website, 2015.

[4] Source for NCD Bio: Narayan, Roger, ed. *Diamond-based materials for biomedical applications*. Elsevier, 2013.

[5] Source: Carpick, R. W., Jackson, A., Sawyer, W. G., Argibay, N., Lee, P., Pachon, A., & Gresham, R. M. (2016). The tribology opportunities study: can tribology save a quad?. *Tribology & Lubrication Technology*, *72*(5), 44.

[6] Source: https://en.wikipedia.org/wiki/Technology_readiness_level

***The technological benefits of material advancements in manufacturing.*** Traditional manufacturing certainly expends a lot of energy and resources. New materials in the form of advanced coatings can lead to economic gains in the manufacturing industry since machining operations often have cutting tools which wear away quickly, expend excessive energy, or thermally damage the part being machined due to improper cooling. However, additive manufacturing (AM) or 3D printing has already been a game-changer, namely in the way companies are designing their future manufacturing strategies to take advantage of the $6B global AM market.

Three-dimensional (3D) printing means there will be a rise of 'mass-customization' instead of the normal paradigm of 'mass manufacturing', where one-size-fits many. AM technologies promise an economic landscape where in many cases, parts can be produced faster, cheaper, yet while expending less energy and wasting less resources. Powder-bed 3D printing consists of the technologies that produce parts or components, slice by slice, by spreading a layer of the desired material in powder form and using different techniques to bind the powder together into a solid 3D final form. While nearly 300,000 consumers have purchases low-cost (sub-$5000) 3D printers, these are not powder-bed 3D printers. The real excitement in terms of next-generation technology is from high-end metal powder-based 3D printers, since many of those can produce direct metal parts. Once you are able to print metal materials, the opportunities for innovating new technologies or re-making old ones are boundless. However, current metal 3D printers print a very limited set of metal materials and usually cannot handle most alloy material systems. While there are numerous impressive-looking metal 3D printers, their ability to print is limited to a small group of metals such as titanium, stainless steel, Inconel (the material from which airplane black boxes are made), aluminum, cobalt chrome, and precious metals such as gold and silver (which is why the 3D printed jewelry industry is exploding).

However, more advanced innovations such as composite materials and graded materials (e.g., a metal sheet that is comprised of two materials which are varied in percentage from one material at one end to the other material at the opposite end). These printers are also super slow and cannot be sped up until fundamental material science questions are answered such as how different powder materials are precisely deformed during sintering, both locally and globally.

***The technological benefits of material advancements in computing.*** Discovered through basic science research over many years, carbon nanotubes (CNTs) are small cylinders whose diameters are about a nanometer in size. They have extraordinary thermal conductivity, mechanical, and electrical properties, and consequently are increasingly being tested as devices in computer chips, such as CNT transistors. A similar carbon related material is graphene, which is 200 times stronger than steel but with high thermal and electrical conductivity. It is also being explored as a new material for computing and many other applications.

**Employing novel approaches to speeding the development of advanced materials.**

***The merit of 'science prize competitions'***. I am aware that one of the new successful strategies for inspiring open innovation and accomplishing idea mining is science prize competitions. My laboratory has participated in a few of them, including being minor beneficiaries of one from an Australian company. It should be recognized that sponsors (whether they be a private, third party 'open innovation company' such as Nine Sigma, a large technology company such as Microsoft, or a federal agency such as DARPA) of such competitions are usually the beneficiaries of upside-down cost-benefit ratios, in comparison to what the academic researchers give up.

For example, I participated in a science competition of a very large high-tech company, who offered to give the 'winners' some new hardware technology and $100K for sponsoring their new idea. Upon developing my proposal, I was about to submit it until I read the fine print which said the sponsor company "*has access to, may have or have had possession of, and/or may create or has created materials and ideas which may be similar or identical in format or other respects. I agree that I will not be entitled to any compensation because of the user of any such similar or identical material …*"

Thus, had I submitted my ideas and not won, the company may still have used it without any expectation of compensation for me or my employer. I hypothesized that they awarded about 5 of 200 submissions, which means they only needed to invest a few hundred thousand dollars for the benefit of an enormous amount of university IP. I question if this is a cunning violation of the Bayh-Dole act which has spawn so much economic success since the 1980s, including some of the most famous university start-up companies (e.g., Google,) around today.

The potential loss of university IP (and the revenues it brings back to the school) are in danger since many academics participate in the current low-odds of winning, basic science research funding environment. I believe the committee should employ careful oversight of non-defense agencies' ability to initiate competitions that university researchers perceive as exploitive. If the sponsor company I encountered had said that they would data mine the submissions for new ideas and contact the proposers about licensing their IP should they find something of interest that would have been a more just outcome and likely would have yielded more proposals. As one ancient Israeli philosopher once said "You must not muzzle an ox to keep it from eating as it treads out the grain.". This means that the workers (in this case, the researchers) should not be muzzled from being rewarded for their work. Unlike almost any other profession, academics have their ideas as their most important asset, and in order for America to remain the global leader in innovation, academic researchers must feel their ideas are protected and even redeemable for reward in the form of licensing, when the ideas are of economic value. We should remember that the Bayh-Dole act was born to remedy a situation where the innovation ecosystem had stalled because idea and IP generation was de-incentivized.

***The merits of university-federal lab/agency partnerships.*** Government laboratories serve many noble purposes for our nation from an academician's viewpoint. First, they provide our government with the research capacity in terms of personnel and equipment infrastructure to tackle the nation's pressing scientific problems, both generally and on-demand. Second, they provide a rich research ecosystem of researchers who care about the science of discovery divorced from the pressures of generating quarterly profits. And third, they provide collaborative resources in terms of intellectual capital, equipment, and mentorship for young researchers.

***Disclosing my own background and educational support as a student.*** Let me start by disclosing that NASA funded my entire education from my freshman year of college at a Historical Black College and University (HBCU), Tennessee State University, until I completed my doctorate at a small, private, technical university in upstate New York, called Rensselaer Polytechnic Institute (RPI). Specifically, it was NASA Glenn Research Center who funded my education through a variety of scholarship and fellowship programs. Over those years, I personally engaged with no less than 50-75 PhD holders and PhD students. They raised the bar for me in terms of what serious scholars were like, what they got excited about, what they did to elevate themselves above the average group of scientists and engineers, and finally, why they were so excited about mastering the literature and writing publications. NASA Glenn, a federal research center, was invaluable to my development as a scholar and researcher.

***Interactions with federal center/labs as a professor and researcher.*** As a Professor and researcher, my lab interacted with two government centers/labs in a major way: (1) NASA Glenn Research Center; and (2) the National Energy Technology Laboratory (NETL).

First, NASA Glenn supported my lab by collaborating with us on a project to test a super-elastic material known as Nitinol. They brought the project to us, and it resulted in several papers, although no direct funding. We were able to leverage their materials processing facilities to fabricate test structures and we engaged with many of their prominent material scientists who went on to write reference letters for my students and convinced them get active in professional technical societies in our field. They also sponsored one of my former students with a NASA GSRP Fellowship, which gave him PhD direct funding and access to resources such as an air erosion tester, high-temperature tribometers (which we do not have access to), and profilometers—all equipment used to test the effects of space dust and contamination on lunar surfaces. Again, the mentorship my former student received was excellent; government labs really do reinforce and accelerate a graduate student's path to research maturity.

Secondly, my major lab interaction has been with the Department of Energy (DOE) NETL lab in Pittsburgh, PA and Morgantown, West Virginia. NETL introduced my lab to the oil and gas drilling problem. They had just purchased a million dollar ultra-deep, high-temperature, high pressure drilling simulator which we could not get access to anywhere else. We were tasked with modeling the phenomena it would measure. They also provided us with wonderful rock samples they machined in-house to allow us to test on our own equipment. As a result, we became reasonably well known in the drilling services industry for our highly complex computer models of the drilling process. NETL also granted us time on their supercomputers and supported postdoctorates in work there NETL. Again, the mentorship was an excellent benefit for my students. I also participated in work involving granular media with the Multiphase Flow group at NETL. I can honestly say that just like many of my other colleagues who work with government labs, their support of our research in indirect and direct ways was pivotal in me progressing up the research path and emerging into a leader in my field, which of course helps with personal things such as promotion up the tenure track. Because of their regional location, they were interested in extending the facilities and resources to universities that were in their region working on research they deemed aligned with their missions. We are grateful to these two labs.

***Other important but less major interactions with federal centers/labs.*** There are also numerous other labs within NASA (NASA JPL and NASA Johnson), and the DOE (e.g., the National Renewable Energy Lab, Argonne, Sandia, Lawrence Livermore, etc.) who have hosted my research group for visits, hired my students, engaged us on data, and written support letters for us to obtain funding from the NSF. We are in conversations with some of these entities because of their vast research capacity and state-of-art equipment (e.g., an open architecture 3D printer for testing new material processes for fusion 3D printers). One of our collaborators performed amazing imaging of single powder micro-particles at Argonne National Lab's Synchrotron X-ray microtomography, where the pores in a single powder particle were visible. Such an instrument is cost prohibitive for most universities. Further, some universities have centers, such as my own university's Energy and Environment Initiative (EEi) that works to connect its own academic researchers with those from federal labs in order to streamline the access to state-of-art infrastructure and collaborations with world-class researchers.

Lastly, some federal labs have even provided guidance to start-up companies such as my own, InnovAlgae. They often help SBIR companies outline the best paths to technology validation, including connecting them to industrial partners that could benefit commercialization efforts.

**The merits of university-company partnerships.**

***Universities use money for basic research to create knowledge, but companies use the knowledge from that same basic research in order to generate money.***

When this cycle is done well, companies who understand the academic research enterprise are pivotal components in the cycle of training, mentoring, graduating, and employing the nation's best and brightest students. However, there are more often than not, a rising tide of companies who struggle to see their crucial role in this cycle. A company that once told me a similar version of the above quote (which I have modified to serve the theme of this testimony) would often want to collaborate with my lab on NSF Grant Opportunities for Academic Liaison with Industry (GOALI) proposals, which are NSF mechanisms to allow research proposals to be a little more applied, and aligned with industry. The partnering company does not have to offer anything more than in-kind contributions which can take on almost any form. Many companies therefore do not spend their resources on the research they seemed to covet for academic labs to generate. Since the NSF engineering program funding rates are around 10-15 percent, it means that my team and my collaborating company would have to submit 7 to 10 proposals over many years (some have a single annual submission window, while others have just two) before a proposal is funded. Of course, most researchers eventually move on and the collaborative opportunity, which are often brilliant ideas, flounders. It would be a game changer if the company were incentivized to invest seed money into the basic research of the project they like.

Yet, when some of these companies have job openings, they often bombard us with emails to get our graduating students. I used to wonder why they expected me to have any students at all when they broke the cycle (i.e., universities use money to create knowledge; companies use the knowledge to generate money). This is not every company of course, but such interaction is common and this committee can help us both the university and company's efforts.

I think the Congress can provide some win-win help here by looking at what some other governments do well, at least in this one area. For example[7], Brazil's government requires oil & gas companies to spend ½ of 1% of their gross revenues from Brazilian oil field production on Brazilian universities.

Perhaps more aggressive tax incentives could be offered to companies who invest in American research universities' basic science research. They can give these universities some percent of their gross revenues and receive increasing tax incentives when they go above some threshold. These companies would

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[7] Source: Andrews, Phil, Jim Playfoot, and Simon Augustus. *Education and Training for the Oil and Gas Industry: The Evolution of Four Energy Nations: Mexico, Nigeria, Brazil, and Iraq*. Elsevier, pp.70, 2015.

benefit from having a stronger American workforce, richer basic research results from which to learn, and the country would benefit by having its capacity for basic research increased.

***A final recommendation for supporting basic research.*** If congress were to inject new funds into the NSF to increase the number of NSF graduate student research fellowships by a factor of two from 2000 to 4000 per year (the total annual number of applicants is typically 14,000) which is likely to increase the NSF fellowship investment from $333M to $666M annually, this would inherently: (1) fund basic research since NSF fellows have academic freedom to work with faculty to choose any project, which will likely be more basic science; (2) strengthen the American science, technology, engineering, and math (STEM) PhD pipeline since the high stipend levels have been shown to motivate more of the nation's 'best and brightest' students to stay in school and pursue doctorates; (3) this would loosen up the tension of the low funding rates for basic science and it will also allow principal investigators to support a diverse range of 'crème of the crop' students from other nations in addition to our own students not supported by the NSF fellowship.