HDIAC Journal
The Journal of the Homeland Defense & Security Information Analysis Center
Volume 4 Issue 4 Winter 2017

Reimagining the Warfighter Exoskeleton

HDIAC Journal
The Journal of the Homeland Defense & Security Information Analysis Center

Volume 4 • Issue 4 • Winter 2017

Director: **Stuart Stough**
sstough@hdiac.org

Deputy Director: **Joseph Cole**
jcole@hdiac.org

About this Publication

The Journal of the Homeland Defense and Security Information Analysis Center (HDIAC) is published quarterly by the HDIAC staff. HDIAC is a DoD sponsored Information Analysis Center (IAC) with policy oversight provided by the Assistant Secretary of Defense for Research and Engineering (ASD (R&E)), and administratively managed by the Defense Technical Information Center (DTIC). HDIAC is operated by Information International Associates (IIa) in Oak Ridge, Tenn. Reference herein to any specific commercial products, processes or services by trade name, trademark, manufacturer or otherwise, does not necessarily constitute or imply its endorsement, recommendation or favoring by the United States government or HDIAC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or HDIAC and shall not be used for advertising or product endorsement purposes.

Table of Contents

ON THE COVER

An Air Force combat controller with the 320th Special Tactics Squadron coordinates with a UH-60 Blackhawk for take off during a humanitarian assistance and disaster response scenario as part of Rim of the Pacific (RIMPAC) 2016, Pohakuloa Training Area, Hawaii, July 10, 2016. Twenty-six nations, more than 40 ships and submarines, more than 200 aircraft and 25,000 personnel are participating in RIMPAC from June 30 to Aug. 4, in and around the Hawaiian Islands and Southern California. The world's largest international maritime exercise, RIMPAC provides a unique training opportunity that helps participants foster and sustain the cooperative relationships that are critical to ensuring the safety of sea lanes and security on the world's oceans. RIMPAC 2016 is the 25th exercise in the series that began in 1971. Photo Illustration created by HDIAC and adapted from U.S. Air Force photo by 2nd Lt. Jaclyn Pienkowski (available for viewing at http://www.24sow.af.mil/News/Article-Display/Article/849001/revive-rescue-repeat-marine-recon-and-air-force-special-operators-hone-humanita/).

AE Alternative Energy | B Biometrics | CBRN CBRN Defense | CS Cultural Studies | CIP Critical Infrastructure Protection | HDS Homeland Defense & Security | M Medical | WMD Weapons of Mass Destruction

Contact

HDIAC Headquarters
104 Union Valley Road
Oak Ridge, TN 37830 • 865-535-0088

Fatena Casey, Technical Office Manager
Jennifer Kruzic, Graphic Designer
Amanda Andrews, Editor
David McCarville, Social & Multi-Media Editor

Marisiah Palmer-Moore
Contracting Officer Representative

DoD Information Analysis Centers
8745 John J. Kingman Road
Fort Belvoir, VA 22060
703-767-9109
marisiah.v.palmer-moore.civ@mail.mil

Michele Finley
Public Affairs Officer

Defense Technical Information Center
8725 John J. Kingman Road
Fort Belvoir, VA 22060
703-767-8215
michele.l.finley2.civ@mail.mil

Message from the Director

Stuart Stough
HDIAC Director

American physicist William Pollard once stated, "Without change there is no innovation, creativity, or incentive for improvement. Those who initiate change will have a better opportunity to manage the change that is inevitable." This is perhaps one of the most exciting times of innovation and change in human history, and the Department of Defense (DoD) remains on the leading edge of this research. The rapid advance of technology provides the DoD various opportunities to enhance and ultimately transform its equipment and capabilities.

Over the last quarter, HDIAC continued to proactively support DoD's R&D and S&T initiatives, as well as current and future requirements across all eight HDIAC focus areas. Through focused research and analysis, HDIAC's journal captures a handful of these developments and illustrates their potential application in future DoD innovation to the DoD, Communities of Interest, and Centers of Excellence.

The DoD remains one of the world's largest energy and fuel consumers; therefore, the development of new technologies and alternative fuels remains critical. From June through August 2016, the U.S. Navy incorporated 77.6 million gallons of alternative fuel blend (from waste beef) to support the Rim of the Pacific naval exercise [1]. GSR Solutions President Anju Krivov provides insightful analysis into biofuel R&D and the implementation of an efficient stream of algal biofuel to power military operations. While challenges persist on the scalability of this technology, the benefits and usage of biofuels remain far-reaching.

In the wake of one of the most devastating U.S. hurricane seasons and the associated impacts on critical infrastructure and fuel supplies, HDIAC Subject Matter Expert Joel Hewett assesses energy resilience. Of the 16 critical infrastructure sectors, the energy sector sustained significant damage resulting in lasting impacts, and the DoD continues to help bring it back online. A presidential policy directive defines resilience in terms of "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions [2]." In preparation for future events and to mitigate a lengthy recovery, Hewett's research highlights developments for storage, facility hardening, and artificial intelligence-assisted modeling.

Next, researchers from the Georgia Institute of Technology explore the transition and applicability of 4-D printing. In essence, this approach to structurally complex 3-D manufactured materials is now entering a new, potentially game-changing phase that incorporates smart materials the producer can pre-program to respond to change or stimulus. The DoD could directly benefit from this technology, applications of which could include manufacturing sensors, self-assembling tents, morphing antennae, and active truss structures. As the military components undergo modernization changes, these technologies potentially offer the DoD another innovative capability to ensure battlefield dominance.

Powered exoskeletons, such as those from Defense Advanced Research Projects Agency and United States Special Operations Command, are technological innovations aimed at physically assisting the warfighter by reducing metabolic costs on the battlefield. Biodesigns has developed a single limb exoskeleton that enhances the warfighter's ease of access to mission-critical equipment while ensuring their ability to perform all combat-related physiological requirements.

Lastly, Deft Dynamics put a new spin on one of the oldest pieces of equipment—the ladder. Ladders remain a critical piece of equipment in military operations and the first responder community, including gaining access to and extracting personnel from confined or restricted spaces. This R&D regarding open-architecture composite structures represents an innovative approach to an old technology that directly impacts both the military and first responder communities. ■

References

1. U.S. Department of Agriculture. (2016, January 20). *77.6 million gallons of alternative fuel blend (from waste beef)* [Press release]. Retrieved from https://www.usda.gov/media/press-releases/2016/01/20/secretaries-navy-agriculture-launch-deployment-great-green-fleet
2. U.S. Executive Office of the President. (2013, February 12). Presidential Policy Directive/PPD-21 -- Critical Infrastructure Security and Resilience. Retrieved from https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

Algal Biofuel Industry Resilienc
in a Low-Priced Crude Oil Envir

Anju D. Krivov, Ph.D.

Introduction

The Department of Defense (DoD) has established ambitious goals for its use of renewable fuels for decades to come, and several national-level initiatives have emerged to aid this transition. In 2010, the U.S. Navy's Great Green Fleet program successfully demonstrated the use of a 50-50 blend of algal biofuel and petroleum as jet fuel for naval aviators, which met or exceeded JP-8 military fuel standards [1]. Additionally, in 2012, the U.S. Department of Agriculture (USDA) collaborated with Airlines for America and Boeing Co. to launch the Farm to Fly initiative, bringing together commercial and military aviation firms to support the U.S. biofuels industry [2]. Half a decade later, after the price of crude oil plummeted from a seemingly sustained high of $100 per barrel to levels chronically under $60 per barrel, several technical and economic barriers remain before advanced biofuels can replace significant amounts of fossil fuels. Further complicating this transition is the retreat of

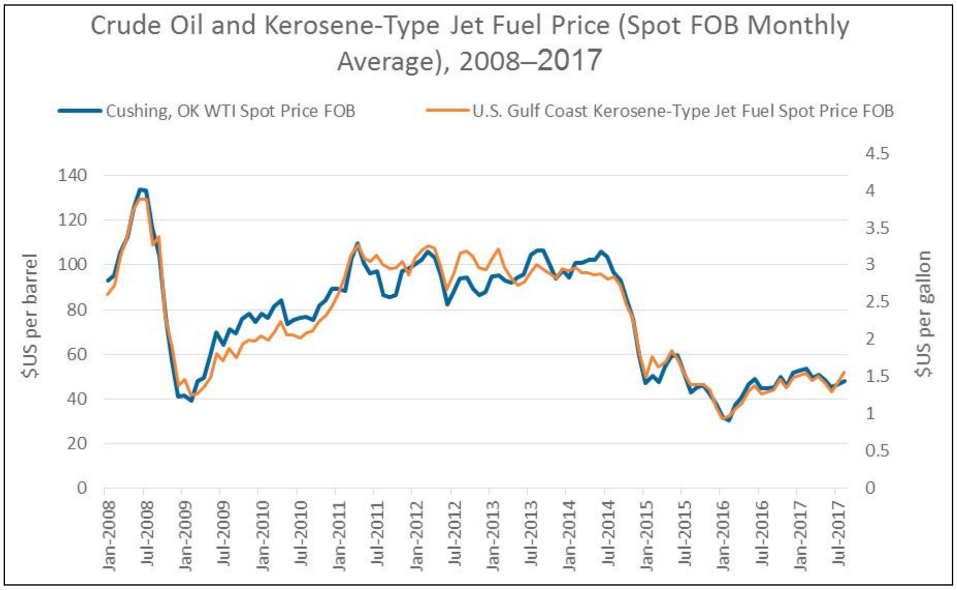


Figure 1: Crude oil and kerosene-type jet fuel price comparison (in nominal dollars). Adapted from [3,4].

several next-generation biofuels firms from the energy space toward other high value markets, including Solazyme (now TerraVia), Sapphire Energy, and Heliae [3].

This recent shift in the economic viability of the algal biofuel industry raises an important question. Which is the narrower bottleneck preventing the widespread commercialization of algal biofuels: an insufficient increase in productivity derived from advances in upstream production from algal strains or the need for an efficient and adequately rich feedstock?

Recent Advances in Algal Biofuel R&D

Despite the sharp drop in crude oil prices since 2014, research and development (R&D) into algal biofuel continues apace in academia and industry alike. Increasing algal oil production at the cellular level has long been a primary target of genetic engineers. At the beginning of 2017, Synthetic Genomics and Exxon Mobil Corp. extended their $600 million agreement, first signed in 2009, to jointly conduct research into advanced algal biofuels. Recently, the Synthetic Genomics team demonstrated a doubling of lipid production in the Nannochloropsis gaditana microalga that, under natural conditions, has a lipid content of approximately 20 percent. It is estimated this newly-engineered strain could produce up to 1,600 gallons of lipids per acre per year, a high level of productivity [4].

While Synthetic Genomics' focus is on increasing oil at the cellular level, researchers at the Pacific Northwest National Laboratory (PNNL) have focused on increasing mass productivity. In 2016, PNNL researchers explicated the mechanism in the Synechococcus strain of algae that allows the strain to triple in size to accommodate a rapid expansion and to flourish under intense light by using energy inputs to keep growing [5]. The importance of this research lies in the efficient coupling of photosynthesis and productivity. This development is central to the advancement of biotechnology applications based on solar energy, and researchers were able to delineate putative biological principles that may allow unicellular cyanobacteria to achieve ultra-high growth rates via photophysiological acclimation and effective management of cellular resources under different growth regimes [6].

The algal-focused Development of Integrated Screening, Cultivar Optimization and Validation Research project is a $6 million joint PNNL-Sandia National Laboratories project designed to determine the toughest and most commercially viable strains of algae, with the goal of identifying four promising strains from at least 30 initial candidates. Additionally, researchers at Los Alamos National Laboratory are focused on understanding the molecular tools, technologies, and resources used in strain improvement; on identifying improved strains; increasing algae biomass productivity, and on increasing the energy-efficiency of algae processing steps.

Challenges in Upscaling Genetically-Modified Algal Strains

In terms of mass algal lipid production, the green colonial unicellular microalga Botryococcus braunii is considered to be a particularly hydrocarbon-rich alga. It can produce C21 to C33 odd numbered n-alka-

Figure 2: Cadet 2nd Class Zachary Bruhn researches algae lipid biofuels in the Life Science Research Center at the Air Force Academy Sept. 26, 2012. Bruhn is assigned to Cadet Squadron 01. (U.S. Air Force photo/Elizabeth Andrews)

dienes, mono-, tri-, tetra-, and pentaenes, and even C40 isoprenoid hydrocarbons [7,8]. However, a slow rate of growth (typical doubling time clocking in at 72 hours [9]) makes it an unpopular candidate for mass culturing—but that could change in the future. In May 2017, the algal genetic engineering community celebrated the genome sequencing of the fuel-producing green microalga B. braunii [10]. It was the first complete genome sequencing of the alga Chlamydomonas reinhardtii that paved the way to the sequencing of B. braunni. This significant step will further help in manipulating the B. braunii cells either to make specific types of oil directly, or by transferring the genes into other photosynthetic organisms to have them produce the oil [10]. How the B. braunni or N. gaditana and other strains might become commercial in scale is another question.

So far, genetically-modified algae have been grown in closed photobioreactors to prevent their escape into natural ecosystems (see Figure 4). However, in 2017, Sapphire Energy, the U.S. Environmental Protection Agency (EPA), and the University of California, San Diego published the first EPA-approved outdoor field trial of a genetically engineered alga, Acutodesmus dimorphus, for fatty acid biosynthesis and green fluorescent protein expression. The 50-day field trial led to the conclusion that genetically engineered algae can be successfully cultivated outdoors, while maintaining the function and persistence of their engineered traits, all without adversely affecting native algae populations [11].

Increasing cellular oil by genetically modifying algae strains has merit as a focus of biofuels R&D, as demonstrated by Synthetic Genomics' effort in doubling the oil content of natural wild strains of algae and by PNNL's research regarding the tripling of algae biomass production for increased oil output. However, these advances in the upstream production of biofuel precursors must be coupled with improvements in providing the algae with an adequate feedstock to allow for efficient growth at a commercial scale.

Purchasing commercially-available nutrients can add a significant cost burden for a biofuels firm. For example, Solazyme's oil-producing alga strain, Chlorella protothecoides, was grown on sugars in fermenters [12]. However, the high cost of using industrial sugars as a feedstock, coupled with severely reduced operating margins stemming from the crash in crude oil prices, led the company to refocus on the health food protein market [3]. Reducing the cost of acquiring feedstock requirements has thus emerged as an important focus of next-generation algal biofuels R&D, with potential outcomes that may rival the genetic engineering of algal strains in its effect on making algal biofuel productive on a commercially sustainable level.

Wastewater as a Feedstock for Algal Biofuel

Wastewater runoff is a known environmental problem that contributes heavily to the eutrophication of its receiving natural water bodies (see Figure 5). This side effect of runoff increases the overall cost of wastewater treatment to cities and municipalities.

A biofuel production pathway based on an oleaginous algal strain, developed by GSR Solutions [13], is being used to capture the free nutrients at the point source of nutrient runoff. This process capitalizes on the presence of excess nutrients in the waste streams. In the

Figure 3: (L-R): Algae slurry; biocrude oil; and, with further processing, refined biocrude which contains mostly the makings of gasoline and diesel fuel. (Source: Pacific Northwest National Laboratory)

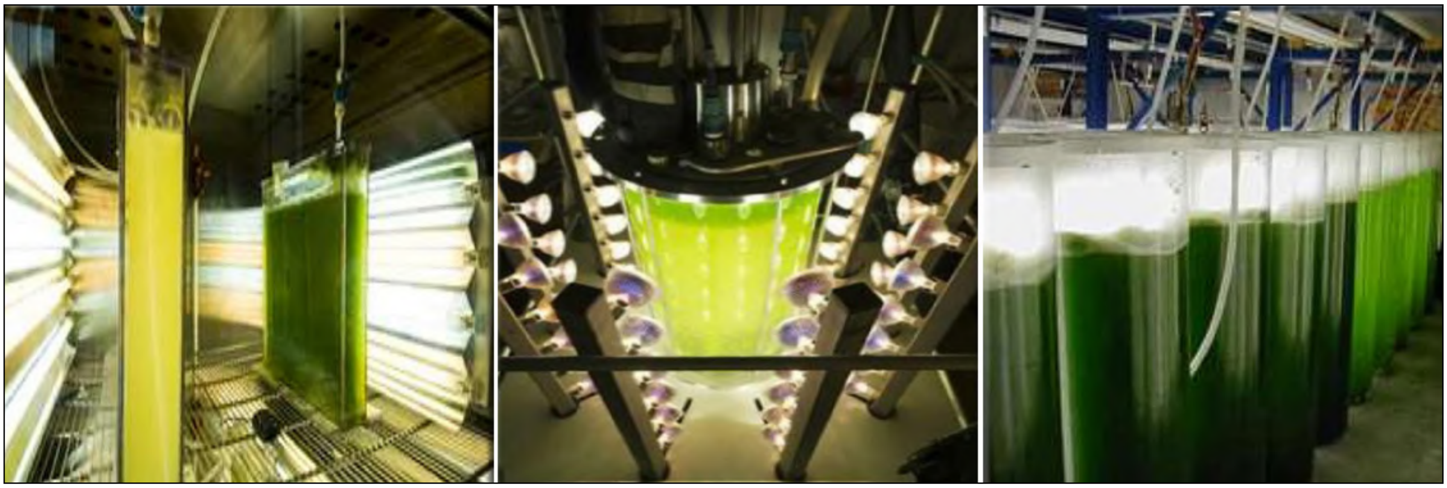


Figure 4: Closed systems. Pictures showing different types of commercially available photobioreactor systems: bags, tubular, vessels etc. (Image courtesey of Robert Henrikson)

long run, it could be a sustainable model for oil and coproducts generation from dairy farm effluents that are typically loaded with excess nutrients, including nitrogen and phosphorus. In 2014, with support from the USDA, GSR Solutions teamed up with local stakeholders and end users of the algal biofuel being produced to bring together the complete supply chain, including members of the Commercial Aviation Alternative Fuels Initiative, the New England Fuel Institute, the Vermont Fuel Dealers Association, and others [14]. The feasibility of using algal biofuel as a crude oil output replacement source in this Northeast-based project was benchmarked to the industry standard, notably, that of Solazyme's oil production levels that were aimed at serving the Navy's Great Green Fleet.

Attempts to grow algal monocultures in high-rate open ponds for periods longer than three months have not succeeded to date, primarily due to the contamination monocultures by wild algae, or by grazing from zooplankton [9]. Naturally-occurring algal assemblages (or polycultures) are low in oil content compared to the monocultures that have been used for dedicated biofuel production sources, and the natural strains are unlikely to match the biofuel production rates demonstrated by Solazyme. For example, the algal assemblage used by Algal Turf Systems for treating wastewater had a fatty acid content ranging from 0.6 percent to 1.5 percent of dry weight, while recovering more than 95 percent of the nitrogen and phosphorous from the culture [15]. Various low-quality wastewater streams, including municipal, industrial, and agricultural (specifically dairy and piggery farms), have been studied for their feasibility as nutrient sources for growing algae [15,16,17], but, so far, no commercial-scale pathway for algal oil production has emerged.

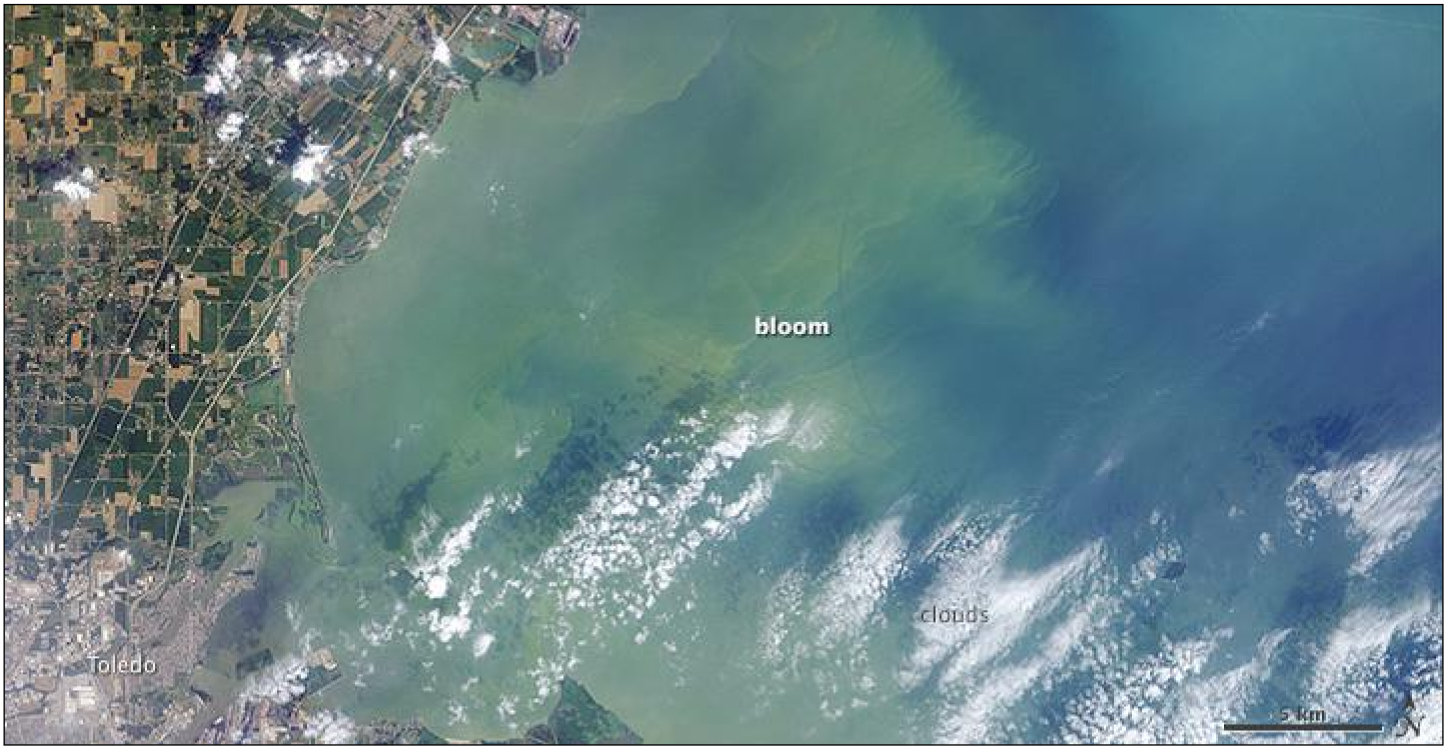


Figure 5: Algae bloom in Lake Erie [20].

Conclusion

Several of the aforementioned groups have turned to wastewater as a feedstock for their algal cultures but none have successfully produced high quantities of the lipids/oil necessary for commercialization. Still, wastewater-integrated systems, in theory, hold great potential for future advances in R&D. In addition to the EPA's well-established regulations for the discharge of dairy farm nutrients, in 2014, the USDA's Biogas Opportunities Roadmap reinforced the need for anaerobic digesters to improve on their nutrient recovery capabilities (particularly nitrogen and phosphorus) from biodigester effluent and solids. GSR Solution's 2014 project using wastewater as an algal oil feedstock—supported by local stakeholders and farms—could serve as a potential model for the sustainable production of biofuel. ■

Acknowledgment

The author is grateful to Richard Altman, Executive Director Emeritus, Commercial Aviation Alternative Fuels Initiative, for his support.

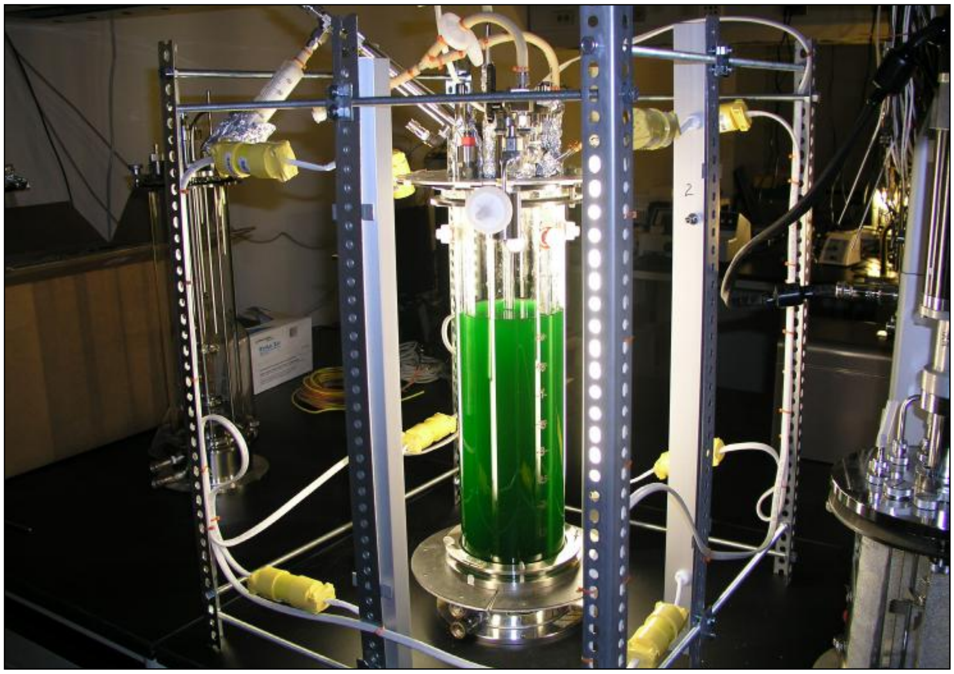


Figure 6: Synechococcus sp. PCC 7002 in a bioreactor [5].

References

1. Currents. (2011, Winter). Retrieved from http://greenfleet.dodlive.mil/files/2011/01/Win11_Great_Green_Fleet_Vision.pdf
2. USDA (2012). Retrieved from http://www.caafi.org/files/usda-farm-to-fly-report-jan-2012.pdf
3. Lane, J. (2017, March 7). The algae chemicals opportunity: The Digest's 2017 multi-slide guide. Biofuels Digest. Retrieved from http://www.biofuelsdigest.com/bdigest/2017/03/07/the-algae-chemicals-opportunity-the-digests-2017-multi-slide-guide/11/
4. Ajjawi, I., Verruto, J., Aqui, M., Soriaga, L., Coppersmith, J., Kwok, K., Peach, L., Orchard, E., Kalb, R., Xu, W., Carlson, T., Francis, K., Konigsfeld, K., Bartalis, J., Schultz, A., Lambert, W., Schwartz, A., Brown, R., & Moellering, E. (2017). Lipid production in Nannochloropsis gaditana is doubled by decreasing expression of a single transcriptional regulator. *Nature Biotechnology, 35*(7), 647-652. doi: 10.1038/nbt.3865
5. Rickey, T. (2016). When the going gets tough, the tough get growing. Pacific Northwest National Laboratory. Retrieved from http://www.pnnl.gov/news/release.aspx?id=4298
6. Bernstein, H., McClure, R., Hill, E., Markillie, L., Chrisler, W., Romine, M., McDermott, J., Posewitz, M., Bryant, D., Konopka, A., Fredrickson, J., & Beliaev, A. (2016). Unlocking the constraints of cyanobacterial productivity: Acclimations enabling ultrafast growth. mBio, 7(4), e00949-16. doi:10.1128/mBio.00949-16
7. Metzger, P., & Largeau, C. (2004). Botryococcus braunii: A rich source for hydrocarbons and related ether lipids. *Applied Microbiology and Biotechnology, 66*(5), 486-496. doi:10.1007/s00253-004-1779-z
8. Dayananda, C., Sarada, R., Kumar, V., & Ravishankar, G. (2007). Isolation and characterization of hydrocarbon producing green alga Botryococcus braunii from Indian freshwater bodies. *Electronic Journal of Biotechnology, 10*(1). Retrieved from http://www.ejbiotechnology.info/index.php/ejbiotechnology/article/view/v10n1-11/200
9. Sheehan, J., Dunahay, T., Benemann, J., & Roessler, P. (1998). Look back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from algae; Close-Out Report. doi: 10.2172/15003040
10. Texas A&M AgriLife Communications. (2017). Genome sequence of fuel-producing alga announced. *ScienceDaily*. Retrieved from https://www.sciencedaily.com/releases/2017/05/170510174850.htm
11. Szyjka, S., Mandal, S., Schoepp, N., Tyler, B., Yohn, C., Poon, Y., Villareal, S., Burkart, M., Shurin, J., & Mayfield, S. (2017). Evaluation of phenotype stability and ecological risk of a genetically engineered alga in open pond production. *Algal Research*, 24, 378-386. doi:10.1016/j.algal.2017.04.006
12. Kanellos, M. (2011, May 6). Solazyme ups IPO price: $18 a Share. Retrieved from https://www.greentechmedia.com/articles/read/solazyme-ups-ipo-price-18-a-share#gs.gfygRYE
13. Dahiya, A. (2011). Cost-effective algae biomass production for oil integrated with wastewater treatment and valued by-product. Environmental Protection Agency. Retrieved from https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/9478
14. Dube, C. (2015, September 11). Can cows, manure, and algae all add up to clean water? Lessons from Charlotte, Vermont [Web log post]. Retrieved from https://www.clf.org/blog/can-cows-manure-and-algae-all-add-up-to-clean-water-lessons-from-charlotte-vermont/
15. Mulbry, W., Kondrad, S., & Buyer, J. (2008). Treatment of dairy and swine manure effluents using freshwater algae: Fatty acid content and composition of algal biomass at different manure loading rates. *Journal of Applied Phycology, 20*(6), 1079-1085. doi:10.1007/s10811-008-9314-8
16. Oswald, W. (2003). My sixty years in applied algology. *Journal of Applied Phycology, 15*(2/3), 99-106. doi:10.1023/A:1023871903434
17. Lundquist T.J., (2008) Production of Algae in Conjunction with Wastewater Treatment. Presentation from the February 2008 National Renewable Energy Laboratory-Air Force Office of Scientific Research joint workshop on algal oil for jet fuel production.
18. U.S. Energy Information Administration. (2017). Cushing, OK WTI spot price FOB (Dollars per Barrel). Retrieved from https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RWTC&f=M
19. U.S. Energy Information Administration. (2017). U.S. Gulf Coast kerosene-type jet fuel spot price FOB (Dollars per Gallon). Retrieved from https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EER_EPJK_PF4_RGC_DPG&f=M
20. NASA Earth Observatory. (2014, August 5). Algae bloom on Lake Erie. Retrieved from https://earthobservatory.nasa.gov/IOTD/view.php?id=84125&src=eorss-iotd

Anju D. Krivov
President, GSR Solutions

Anju Krivov is the president of GSR Solutions. She also teaches Waste to Energy, Nutrients Recovery and Food Waste to value courses at the University of Vermont, is an advisor to the Buckminster Fuller challenge program, and a member of the Lee Enterprises Consulting Group.

Liquid Fuels Supply

Rethinking Energy Resilie
Wake of Hurricanes Harv
and Maria

Joel Hewett

Introduction

Although Houston is commonly known as “The Bayou City,” some would prefer it to be known as “The Energy Capital of the World.” Of only moderate size when oil was first discovered in Texas in 1894, Houston and its environs now encompass the production, processing, and transportation of massive volumes of crude oil and natural gas [1,2]. It leads the world in petrochemicals research and development and is home to the best and brightest engineers and pioneers of the energy industry [1]. Nearby, underground salt caverns capable of storing 700 million barrels of oil host the jewel of the nation’s energy security infrastructure, the Strategic Petroleum Reserve [3], and local fabrication yards launch massive, floating deep-water production platforms to pump oil from two miles below the surface of the Gulf of Mexico [4].

Yet the industrial heart of the energy economy clustered around Houston and the Gulf Coast between Corpus Christi, Texas, and New Orleans, Louisiana, is not the extraction of crude oil, but its refinement [1]. As of January 2017, more than 52 percent of the nation’s petroleum refining capacity was located along the Gulf Coast, concentrated especially near the borders between Texas, Louisiana, and Mississippi [5]. Located an hour’s drive east of Houston, the city of Port Arthur is home to the Motiva plant, which, with a maximum running capacity of more than 600,000 barrels of crude oil per day (bbl/d), is the largest refinery in the United States [6]. When translated from barrels of oil into gallons of gasoline, the Motiva plant processes 11.4 million gallons of motor gasoline for use on American roads and highways every day [7,8].

This concentration of the petroleum industry and its downstream assets in the Houston-Beaumont area yields considerable economies of scale for investors and consumers alike—but it also makes the region vulnerable to natural disaster events [9]. These massive and complex refining facilities faced such a threat in the late summer

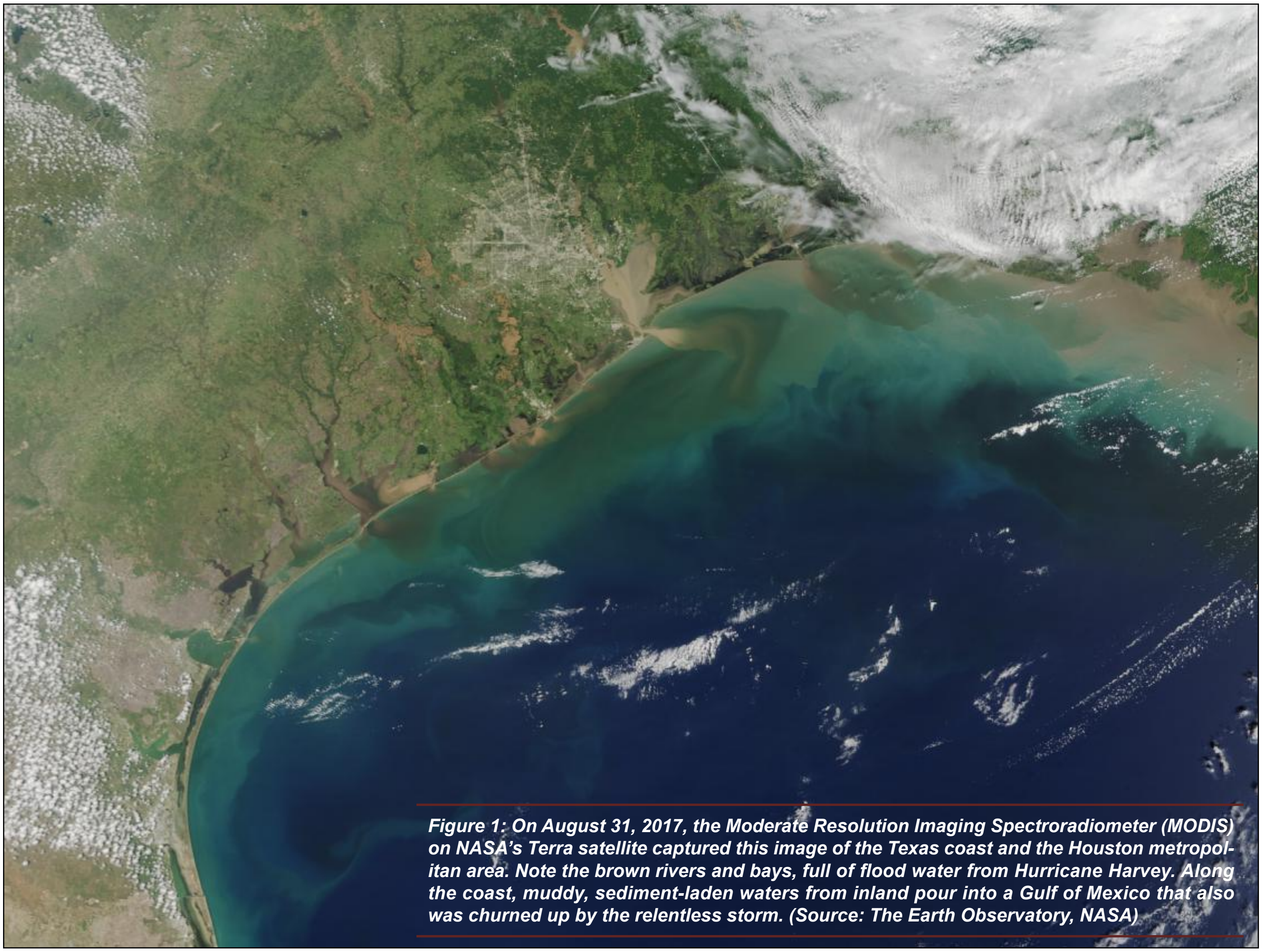


Figure 1: On August 31, 2017, the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite captured this image of the Texas coast and the Houston metropolitan area. Note the brown rivers and bays, full of flood water from Hurricane Harvey. Along the coast, muddy, sediment-laden waters from inland pour into a Gulf of Mexico that also was churned up by the relentless storm. (Source: The Earth Observatory, NASA)

of 2017, as Hurricane Harvey slammed into the Texas coast August 25, 2017 [10]. While still a large Category 4 storm (on the Saffir-Simpson scale), it pushed into the Texas Coastal Bend and then meandered northeasterly along the coast toward Louisiana before hovering over Houston, ultimately dumping an estimated 33 trillion gallons of water onto the coastal plains [11].

A swath of land 3,600 square miles in area between the Houston Ship Channel and the city of Beaumont was hit hardest, receiving more than 40 inches of rain in seven days—an amount just inches shy of what Houston averages in a single year [1,12]. Port Arthur took on an unprecedentedly high 47 inches of rain [12], inundating and shutting down the Motiva refinery. The plant did not start up its crude distillation units to their minimum operating rates for 16 days after Harvey made landfall [13].

At its peak, an estimated 27 percent of the nation's petroleum refining capacity (equivalent to 4.8 million bbl/d) was inoperable due to Hurricane Harvey and its rainfall. Two weeks later, 10 percent of its refining capacity remained offline[14]. Nationwide, the average retail price of finished motor gasoline jumped 30 cents per gallon [15], and the Gulf Coast saw "widespread" gasoline shortages at retail stations, even after the water receded [16]. Gas stations in Dallas, Texas, 225 miles away, either ran dry or saw half-hour wait times at their pumps [16]. A handful of fistfights broke out over the shortages [17]. The primary conduit of refined products running from the Gulf Coast to the Southeast was shut down in part due to damage from the storm, but also because there simply wasn't enough fuel to pump through the pipeline [18,19]. Port closures only exacerbated difficulties, and suppliers as far north as Chicago had problems securing fuel supplies [20,21]. In total, Hurricane Harvey took "a third of U.S. refinery capacity [offline] for days on end," one prominent energy expert noted after the storm. "The hurricane did what terrorists could only dream of" [22].

Energy Resilience

The energy system at large is one of the nation's 16 sectors of critical infrastructure, which the Department of Homeland Defense (DHS) defines as those "assets, systems, and networks…so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof" [23]. Since 2013, a major programmatic goal of DHS has been to improve the overall resilience of the nation's critical infrastructure, which a presidential policy directive has defined as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" [24,25].

The Department of Defense (DoD) is charged with assisting civil authorities in responding to major domestic incidents, as it did after Harvey, in response to Hurricane Irma (which struck Florida September 10, 2017), and after Hurricane Maria (which hit Puerto Rico September 20, 2017) [26]. Because stable access to energy supplies underlies a military installation's resilience, any potential disruption in the energy system is of particular concern to both DHS and DoD [24,26,27]. In 2015, the first-ever Quadrennial Energy Review characterized the mitigation of energy disruptions as being no less than "fundamental" to infrastructure resilience, because of the growing dependency of other critical infrastructure sectors on the energy system [6]. Indeed, when DoD's Defense Logistics Agency (DLA) began preparations for Harvey's landfall, one of the first acts it took was to stage 160 tanker trucks carrying gasoline and diesel fuel at Fort Hood, Texas, to support Federal Emergency Management Agency relief efforts [28].

However, much of the energy-related literature focused on critical infrastructure and resilience is aimed at protecting and restoring the nation's electrical generation, transmission, and distribution network (known collectively as "the grid") [6,24,29,30]. DoD efforts aimed at improving energy resilience also typically address electrical power, specifically on military bases [31]. The deployment of advanced command and control "smart" technologies—as well as large investments by electric utilities for hurricane preparedness—has yielded significant improvements in the resilience of electrical power systems. After Hurricane Irma, electrical service was restored in Florida significantly faster than after Hurricane Wilma hit the state in 2005, even though nearly twice as many total customers lost power due to Irma [32]. The widespread addition of variable electricity generation capacity (from renewable sources like wind or solar) has also made the grid more resilient in the face of disruption [33].

Far less attention has been paid to the resilience of the nation's petroleum processing and transportation sectors—especially to the continued provision of refined petroleum products in disaster zones [34]. The petroleum industry along the Gulf Coast has successfully coped with major tropical storms and hurricanes for decades [35], mostly because the same geographical characteristics that make the region attractive for oil and gas firms—proximity to marine export terminals, and low, flat spaces for petrochemical plant siting—make the area vulnerable to storm damage [1,22]. Hurricanes Katrina and Rita, which struck the Louisiana and Texas coasts in 2005, made those vulnerabilities clear. Together, they caused an unprecedented shutdown of 30 percent of the nation's refinery capacity, and—as happened in the wake of Harvey—gasoline prices spiked around the country [6,27]. Since 2005, largely as a result of the shale oil boom, the concentration of the nation's downstream infrastructure along the Gulf Coast has only intensified [36].

Petroleum processing facilities are a major component of the Department of Energy's (DOE) management of the federal National Infrastructure Protection Plan for the energy sector [23]. Liquid petroleum fuels will remain a major source of power in the United States for decades to come. In 2016, finished motor gasoline (excluding diesel gasoline) represented 18 percent of total primary delivered energy consumption, in any form, in the United States, and DOE's Energy Information Administration (EIA) projects that figure to remain above 15 percent through at least 2026 [37]. In the transportation sector, finished motor gasoline accounts for 61 percent of total delivered energy, with the bulk of the remainder accounted for by diesel for both automotive and off-road use (typically in locomotives) [37]. In Fiscal Year 2014, DoD consumed 87.4 million barrels of fuel in supporting and deploying missions worldwide, including training and other domestic operations [38]. In the event of natural disasters like Hurricanes Harvey, Irma, or Maria, emergency response and recovery vehicles—whether civilian, federal, or military—will operate almost exclusively on refined liquid petroleum fuels.

The Strategic Petroleum Reserve

The comparison between the effects of Hurricane Harvey in 2017 and those of the one-two punch from Katrina-Rita in 2005 is an instructive one. Both storm events inflicted major damage on petrochemical infrastructure, shutting down refineries for weeks and causing the release of millions of pounds of industrial chemicals and hydrocarbons into the environment [22,39]. Both events also triggered the use of the Strategic Petroleum Reserve (SPR) [3]. Constructed in 1977, the SPR is a government-owned series of deep underground storage facilities carved out of the large salt deposits that naturally pockmark the Gulf Coast [3]. Four SPR storage sites dot the Texas and Louisiana coast, each hold-

Figure 2: Airman 1st Class Daniel Langer, a 92nd Logistics Readiness Squadron fuels distribution operator, pulls fuel flow sensing lines from an R-12 Fuel Truck in preparation of a KC-135 Stratotanker aircraft refueling operation March 2, 2015, at Fairchild Air Force Base, Wash. Fuels distribution operators work in the Petroleum, Oil and Lubricants flight responsible for filling KC-135 Stratotankers with fuel both for aircraft use and refueling other planes from all branches of the U.S. military as well as some from allied nations. (U.S. Air Force photo/ Capt. David Liapis)

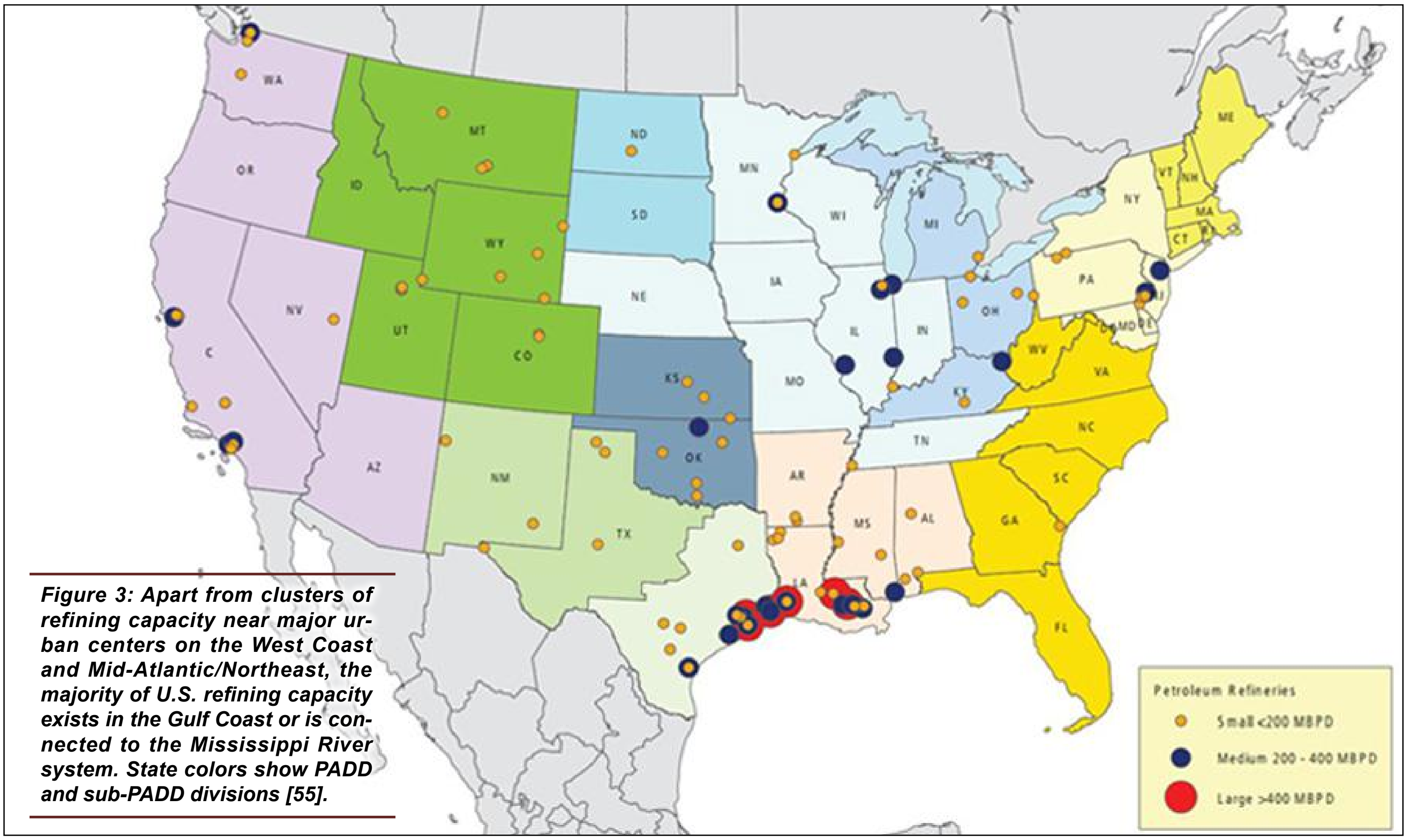


Figure 3: Apart from clusters of refining capacity near major urban centers on the West Coast and Mid-Atlantic/Northeast, the majority of U.S. refining capacity exists in the Gulf Coast or is connected to the Mississippi River system. State colors show PADD and sub-PADD divisions [55].

ing between 70 and 250 million barrels of unrefined crude oil [3].

Connected to pipeline, rail, and marine terminals, SPR oil releases can be directed to commercial refineries or to tankers for ocean-going export [40]. At current rates of national consumption, the SPR holds enough crude to supply the country for approximately 33 days [18]. After the devastation of Hurricane Katrina, DOE approved six emergency requests from refiners to access crude oil supplies, totaling 9.8 million barrels. Days later, an additional 30 million barrels were authorized for release and offered for sale, but only 11 million barrels of that total were purchased by commercial entities [40]. In 2017, less than a week after Hurricane Harvey made landfall in Texas, DOE released 500,000 barrels of crude oil from the West Hackberry SPR site in Louisiana, directed to the Phillips 66 refinery in Lake Charles [18]. DOE later authorized the future release of an additional 5 million barrels to local refineries, if needed [41].

The SPR is a critical contributor to the energy security of the United States and its ability to respond to terrorist attacks, overseas conflicts, and natural disasters [40]. In the case of Harvey, however, where the critical facilities required to process crude oil from the SPR into usable products suffered relatively extensive damage, the release of SPR crude had but limited effect [42].

After Harvey, there was an abundance—not a shortage—of crude oil available. Damage to marine oil delivery terminals on the Gulf Coast temporarily prevented tankers from delivering their product, leaving 28 tankers containing more than 18 million barrels of oil idling in a holding pattern nearby; the delivery ports reopened long before the refineries could return to normal operations [43]. Even though crude production from offshore fields in the Gulf of Mexico was depressed due to the storm, the number of disabled refineries meant that those still operating generally had ample oil at their disposal [36,44]. Nationwide, commercial crude oil inventories before Harvey's arrival were already higher than the annual average for the August/September period, and the availability of oil was reflected in lower prices for West Texas International crude [44,45].

Even the releases of SPR crude after Hurricane Katrina were not made to directly relieve an oil supply crunch but occurred as part of a coordinated release with the International Energy Agency (IEA). In exchange, the IEA released stocks of refined petroleum products to fill a major gasoline supply gap in the southeastern United States [6,36]. Moreover, had a domestic oil supply crunch been urgent, the SPR was not well-placed to provide timely help, as it suffered "significant" damage from Katrina, taking 20 days for its first release of crude to physically move out of SPR terminals [6]. Deliveries of the IEA's refined products imported from Europe also arrived with some difficulty, as much of the Southeast had to be supplied through truck shipments made hundreds of miles inland from Atlantic ports [6,9]. DoD continued supplying refined liquid fuels for Hurricane Katrina relief efforts in Louisiana, Mississippi, Texas, Alabama, and Florida for more than 18 months [46].

Strategies to prevent or mitigate such acute shortages of motor gasoline are likely to fall along one of two lines [47]. First, refinery facilities can be hardened against hurricane-force winds, storm surges, and extreme rainfall totals [6]. Second, strategic, government-owned or -managed stocks of finished motor gasoline can be established at critical points in the petroleum distribution network, providing on-demand supplies of the fuel in a manner similar to the SPR. Recent advances in research and development related to each strategy are discussed below.

Hardening Refinery Facilities

The unique, rainfall-heavy nature of Hurricane Harvey demonstrated not all major storm

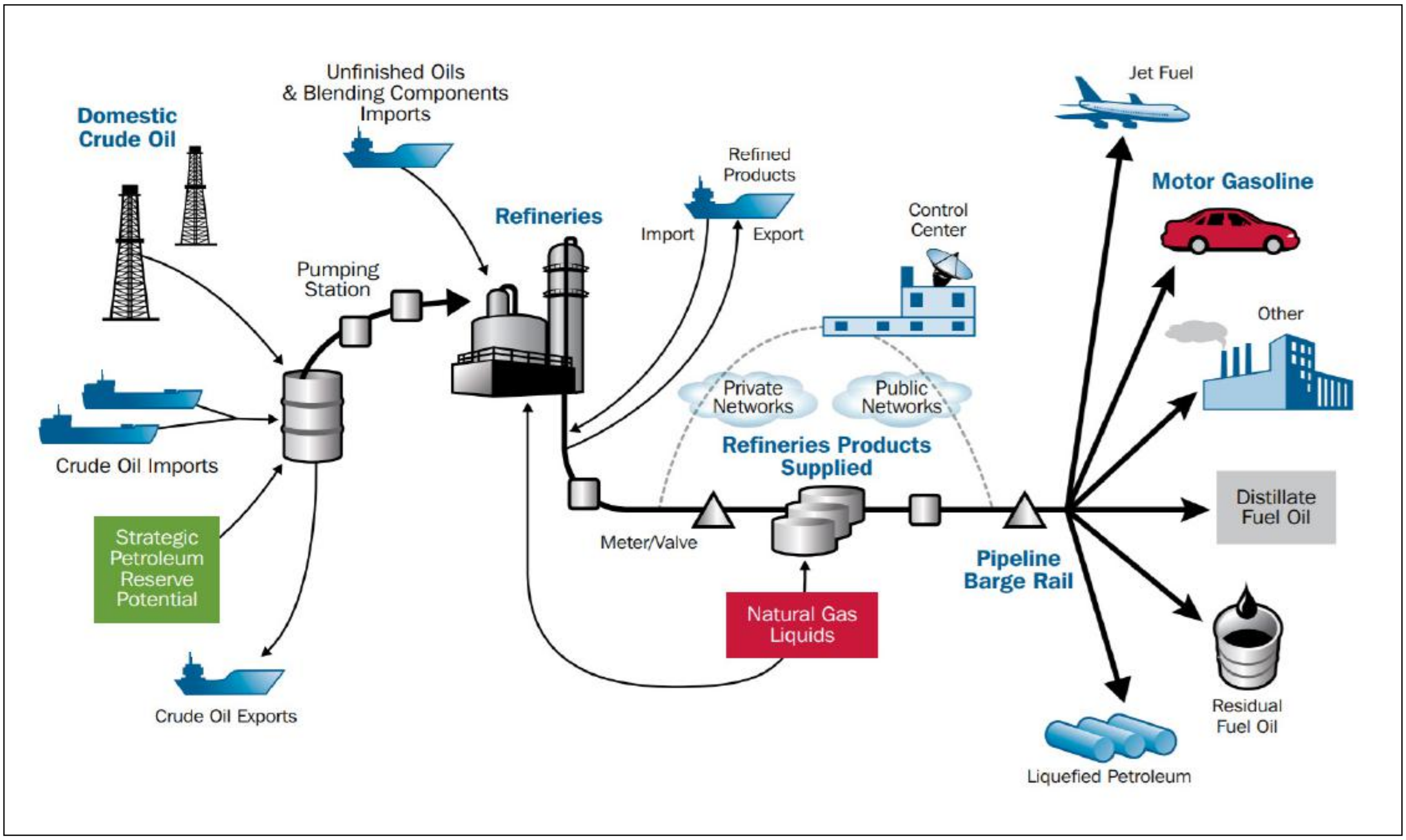


Figure 4: Overview of the petroleum exploration, production, refinement, and distribution networks. Note how refineries are the linchpin—or bottleneck—for the supply of liquid fuels [74].

events are created equal. During Katrina and Rita, although refineries sustained some damage from high winds and rain, the primary source of damage was storm surge-related flooding [36]. Where product storage tanks failed, wind was typically the culprit [48]. The storms ripped off pieces of insulating cladding from many storage tanks before turning them into high-speed airborne projectiles [48]. Refineries shut down as they lost access to electrical power from the grid; only after power was restored could the plant begin the lengthy process of black-starting its equipment [9,27]. After the 2005 hurricane season, downstream operators took substantive steps to remedy these risks, and came through Hurricane Ike in 2008 relatively unscathed [36].

Many plants installed wind braces and structural girders on key pieces of equipment post-Katrina, and a limited number installed portable emergency generators to power critical command and control equipment during outages [49]. The most substantive changes included the building or strengthening of berms and levees around the plants, and the raising of control rooms above expected storm surge levels [6,49]. However, Hurricane Harvey presented a unique threat to Gulf Coast infrastructure, one to which the lessons learned after Katrina and Rita were not applicable. With Harvey, it was extreme levels of flooding—due to the storm's unexpected loitering over Houston and its unprecedented total rainfall—that caused most refinery damage [50]. Harvey's rain both flooded refineries sited outside of storm surge areas, and exacerbated flooding at plants within it. This suggests that refineries located inland of even the most powerful storm surge may require storm hardening preparations that include high-capacity water drainage pumps, for example, to "bail out" drowned equipment [47].

Many of the technologies best suited to "hardening" a refinery have less to do with protecting it from storm damage—which is not cost-effective on a wide scale—than they do with allowing for the quick restoration of operations, a key component of resilience. Second to the draining or removal of floodwaters, the next most important post-storm action for a plant is to restore its sustained access to electrical power.

In 2017, the second installment of the DOE-sponsored Quadrennial Energy Review stressed the need for a "strategic transformer reserve" designed to help restore damaged electrical power transformers and/or substations [30]. Because replacement transformers can take many months to fabricate and assemble, a downed substation is a critical vulnerability to energy system resilience. Teams from the DHS Science and Technology Directorate have teamed up in recent years with operators and manufacturers in the power industry to test a rapid response capability to provide replacement 345-kilovolt transformers, with promising results [30]. More applicable to a Hurricane Harvey-like situation, though, are recent design concepts that seek to integrate a replacement transformer fully into a modularized tractor-trailer, or even a train locomotive—allowing for mobile and truly rapid restoration of power to facilities otherwise inaccessible to work crews [30,51].

Extended Gasoline Storage

A shortage of refined petroleum products like motor gasoline has been shown to have deleterious effects on post-disaster recovery and relief efforts [52]. While midstream petroleum companies keep somewhat significant volumes of gasoline in reserve, these inventories function only as working stock. In other words, they are quickly dispatched to respond to just-in-time shifts in regional demand, and such inventories may amount to just a few days' supply at best [19]. In response to Hurricane Harvey, refineries in the Northeast opted to redirect their expected gasoline receipts down to the southeastern United States, the Caribbean, and Mexico, to compensate for the lack of gasoline exports from the Gulf Coast [19]. By doing so, they quickly used all gasoline volumes stored as working inventory; at least two refinery distributors in the area had completely run out of gasoline less than a week after Harvey made landfall [19].

After "Superstorm" Sandy hit New York City in October 2012, first responders experienced a severe crunch in their access to motor gasoline. Refineries, pipeline nodes, and other parts of the petroleum distribution network were flooded, damaged, or lacking power; as a result, New York City suffered widespread gasoline shortages, lasting up to 30 days in some locales [53]. First response and other recovery efforts, even with priority access, suffered from the shortage [6,54]. Two refineries in New Jersey were shut down for over three weeks, with a combined capacity of 300,000 bbl/d, while four others were forced to operate at lower rates [53].

In order to prevent a similar scenario from reoccurring, in 2014 the DOE collaborated with the DLA within DoD to set up storage and distribution facilities for four stockpiles of refined motor gasoline [55]. The Northeast Gasoline Supply Reserve (NGSR), as the terminals came to be known, holds one million barrels of gasoline, and has further resilience-oriented characteristics built into its operation. Each terminal, for instance, must have backup electricity generation on-site, and multiple methods for exporting gasoline in the event of an emergency (whether by truck, pipeline, or marine vessel) [56].

The NGSR is not the first time of a domestic refined fuel supply has been established in the United States. In 2000, DOE set up a similar system, the Northeast Home Heating Oil Reserve (NEHHOR), a series of three terminals between New Jersey and Massachusetts that holds one million barrels of heating oil, or approximately 10 days of supply [57]. In fact, the NEHHOR was tapped for the first time during Sandy, and DLA personnel moved roughly four million gallons of heating oil for distribution in the storm's wake, from the NEHHOR and other stocks [56,58].

The NGSR holds tremendous benefits for resilience, especially in the guaranteed provision of gasoline to first responders, including any active military or reserve troops called up to assist in responding to a major disaster. However, with even a million barrels stored, if tapped, the NGSR could supply the East Coast for only about eight hours' worth of consumption [19].

Gasoline is a highly refined product of crude oil, and unfortunately for those who might wish to store it for extended periods, begins to degrade as soon as it is produced [59]. Gasoline easily evaporates at room temperatures, and over an extended period, oxidation of the fuel breaks down its long-chain hydrocarbons (C4 to C12) and increases the amount of polymeric "gum" present in the fuel [60]. Successful storage of refined products like gasoline incurs significantly higher per-barrel costs than crude oil, and requires, at minimum, continual rotation and replenishment of inventories [61]. Technical and economic methods to do so have been modeled in the past [62], and the NGSR has to date proved a technical and strategic success.

Scientific research into the chemical and physical causes behind liquid fuel degradation has advanced in the past three years in particular [63], and work completed in September 2017 has demonstrated experimentally that gasoline storage containers lined with tin resist fuel degradation better than containers fabricated wholly from steel or polyethylene, two materials commonly used in the petroleum industry [60]. Further research into the mechanics of extended gasoline storage may make the deployment of strategic refined fuels reserves significantly less costly.

Figure 5: Chalmette, New Orleans, LA, 9-16-05 -- Thick Oil is leaking from the storage facility in Chalmette into the surrounding neighborhood. Thousands of people have been displaced by Hurricane Katrina. (Source: FEMA/Marvin Nauman)

Artificial Intelligence-Assisted Modeling

The suite of software and technologies known as artificial intelligence (AI) also shows exceptional promise in aiding both meteorological and energy experts in modeling scenarios related to hurricane damage and gasoline supply. AI-assisted models and simulations can allow for more advanced prediction capabilities than are currently available in tropical storm- or hurricane-level forecasting [64]. They may also provide human operators with a better-informed suite of potential hazards or scenarios upon which to base appropriate risk assessments.

For instance, the possibility that a powerful storm the size of Harvey would linger for days—or follow an odd, dual-landfall storm track—did not appear a likely scenario before August 2017 [47]. In 2015, researchers at Sandia National Laboratories conducted a major study of the nation's liquid fuels production and distribution infrastructure, using a series of high-powered computer models to simulate seven events that could stress the system [65]. Using inputs from the National Transportation Fuels Model and models from the National Infrastructure Simulation and Analysis Center, the Sandia team assessed how a hypothetical Category 5 hurricane that made landfall directly over Houston would affect the liquid fuels system.

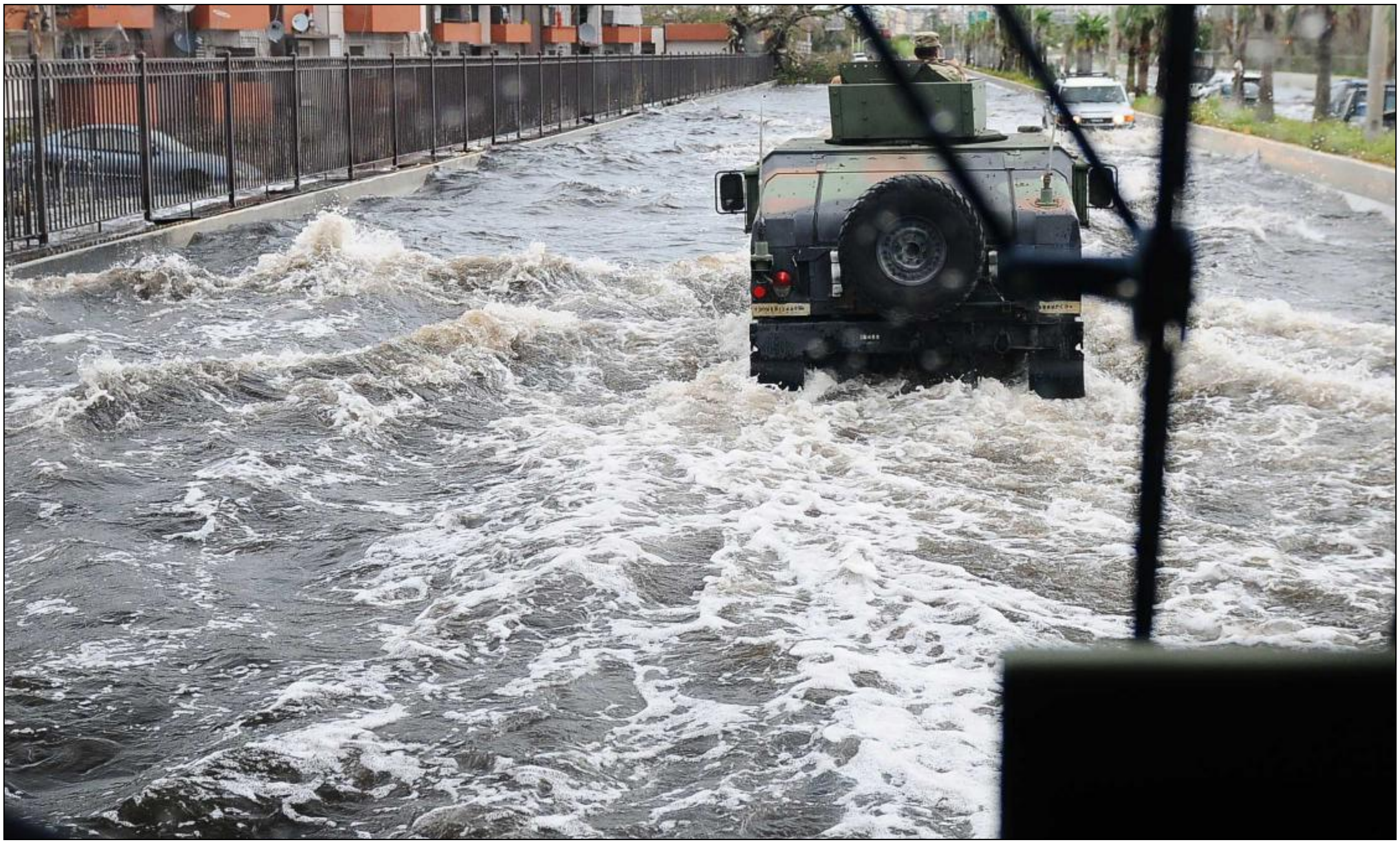


Figure 6: Puerto Rico National Guardsmen patrol a highway in Carolina, Puerto Rico, Sept. 22, 2017, after Hurricane Maria caused extensive flooding. (Puerto Rico National Guard photo/Sgt. Jose Ahiram Diaz-Ramos)

Most notably, the study modeled just four refineries in the Beaumont-Port Arthur area would be inundated; those refineries have a total capacity of 1.5 million bbl/day of crude oil [65]. While the study also accounted for fairly widespread electrical grid outages, it underestimated the amount of rainfall, rather than storm surge alone, that could substantially flood plants and shut down refinery operations [65]. And, notably, the scenario assumed always a straight-track progression of the storm, from the Gulf of Mexico to the interior of Texas.

A similar scenario analysis performed in 2014 for DOE also analyzed the effects of a major storm striking the heart of Galveston Bay and Houston, as Hurricane Harvey did [53]. This model posited that a Category 3 storm, also following a straight-track storm progression, would shut down between 1.1 and 4.5 million bbl/day of refining capacity; a large and unwieldy range [53].

Finally, AI-assisted energy models could help to significantly reduce the cost and infrastructural burden of systematically storing refined gasoline reserves at critical nodes [64]. DLA Energy is currently collaborating with the University of Arkansas Center for Excellence in Logistics and Distribution (CELDi), in order to build out and test a major network simulation model, for DoD to use in determining fuel choke points for both normal and wartime operations [66]. A CELDi-type model, integrating select AI components, could optimize the structure, geography, and fuel-refresh characteristics of a dedicated gasoline reserve system like the Northeast Gasoline Supply Reserve, potentially on a wider scale.

Conclusion

Hurricanes Harvey, Irma, and Maria dealt a strong, but nowhere near fatal, blow to the United States' domestic supply of motor gasoline. However, both refining capacity and distribution systems have come under great strain in response. Weeks after Hurricane Harvey's landfall, as the Gulf Coast's refineries slowly returned to life, commercial gasoline and distillate inventories in the United States were drawn down to their lowest levels in years [67]. Those low inventories have come at the same time that the United States is exporting record-high volumes of crude oil, at just under 1.5 million barrels per day near the end of September 2017 [68]. Florida felt such an acute shortage of gasoline in some places that some local and national leaders have already called for the establishment of a "Florida Gasoline Supply Reserve" [69,70]. In the American territory of Puerto Rico, the devastation wrought by Hurricane Maria has irreparably destroyed the island's electrical system. However, the need for refined petroleum fuel products is far more severe than that for electricity [71]. Low gasoline inventories on the island ahead of the storm, broken distribution networks, and damaged marine oil terminals have made gasoline and diesel fuel as good as "liquid gold" in Puerto Rico [72].

The resilience of the nation's supply of liquid fuels is likely to receive much attention in the years to come. Already, the National Petroleum Council, a federal advisory committee established in the 1940s, has initiated a study at the request of DOE into the changing dynamics of the United States' oil and natural gas transportation infrastructure [73]. Its charge is to determine just how vulnerable—or resilient—the petrochemical industry concentrated along the Gulf Coast is to major storms or other infrastructure disruptions [73]. ■

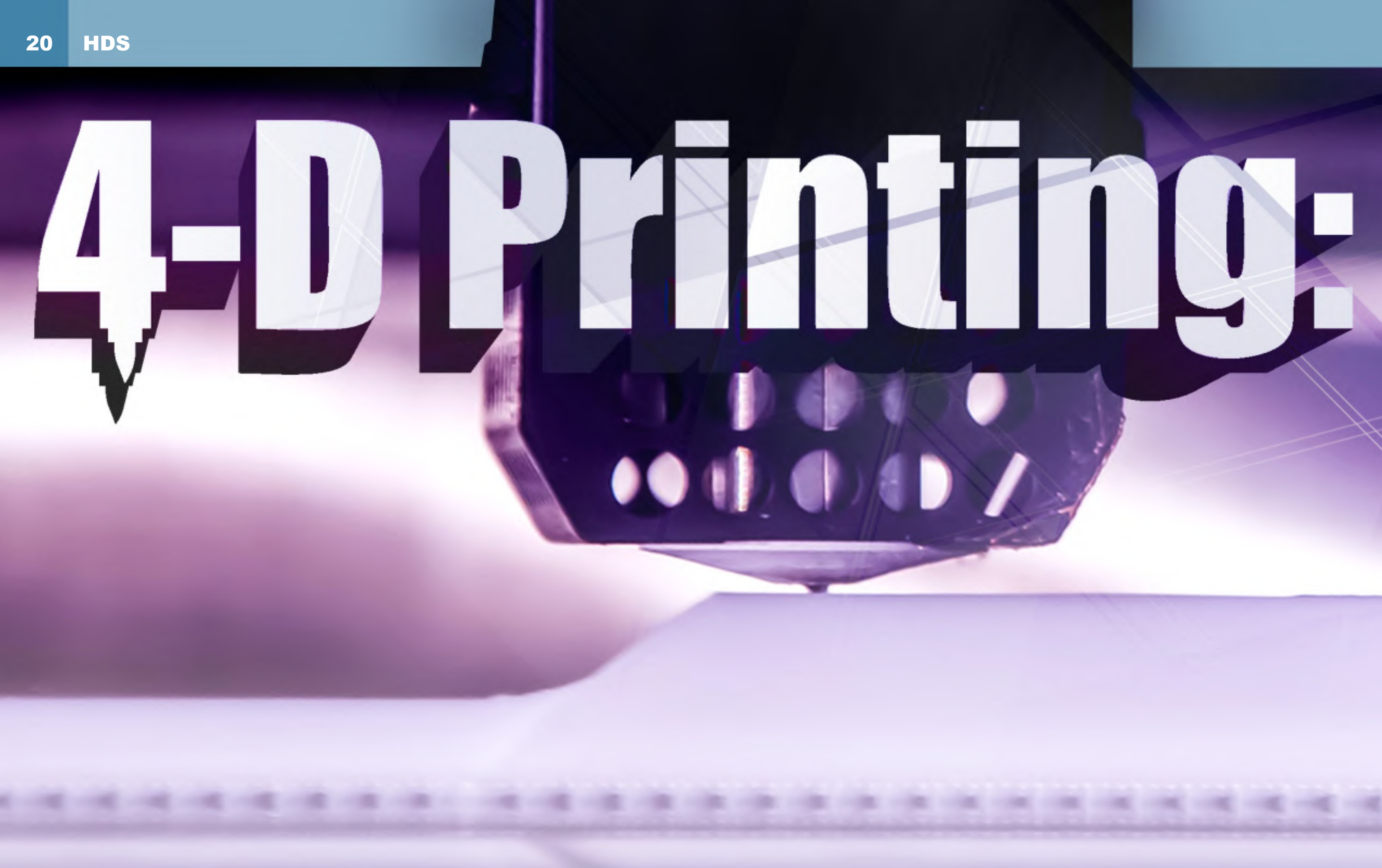
References

1. Melosi, M., & Pratt, J. (2007). Introduction. In M. Melosi and J. Pratt (Eds.), Energy metropolis: An environmental history of Houston and the Gulf Coast. Pittsburgh, PA: University of Pittsburgh Press.
2. American Oil & Gas Historical Society. (2017). First Texas oil boom. Retrieved from https://aoghs.org/petroleum-pioneers/texas-oil-boom/
3. U.S. Department of Energy. (2017, July 31). SPR Quick Facts and FAQs. Retrieved from https://energy.gov/fe/services/petroleum-reserves/strategic-petroleum-reserve/spr-quick-facts-and-faqs
4. Priest, T. (2007). The offshore imperative: Shell Oil's search for petroleum in postwar America. College Station, TX: Texas A&M University Press.
5. U.S. Energy Information Administration. (2017, June 21). Refinery Capacity Report, June 2017. Retrieved from https://www.eia.gov/petroleum/refinerycapacity/refcap17.pdf
6. Quadrennial Energy Review (QER) Task Force. (2015, April 21). Quadrennial Energy Review: Energy transmission, storage, and distribution infrastructure. Retrieved from https://www.energy.gov/sites/prod/files/2015/07/f24/QER%20Full%20Report_TS%26D%20April%202015_0.pdf
7. U.S. Energy Information Administration. (2017, June 22). Top 10 U.S. refineries operable capacity. Retrieved from https://www.eia.gov/energyexplained/index.cfm?page=oil_refining#tab4
8. U.S. Energy Information Administration. (2016, November 1). Petroleum products produced from one 42-gallon barrel of oil input at U.S. refineries, 2015. Retrieved from https://www.eia.gov/energyexplained/index.cfm?page=oil_refining#tab3
9. O'Very, G.B., Jr. (2007, March 24). Geographic concentration of oil infrastructure: Issues and options (Master's Strategy Research Project, U.S. Army War College). Retrieved from http://handle.dtic.mil/100.2/ADA471322
10. Fernandez, M., & Blinder, A. (2017, August 25). Hurricane Harvey makes landfall near Corpus Christi, Tex. *New York Times*. Retrieved from https://www.nytimes.com/2017/08/25/us/hurricane-harvey-texas.html?mcubz=0&_r=0
11. Fritz, A., & Samenow, J. (2017, September 2). Harvey unloaded 33 trillion gallons of water in the U.S. *Washington Post*. Retrieved from https://www.washingtonpost.com/news/capital-weather-gang/wp/2017/08/30/harvey-has-unloaded-24-5-trillion-gallons-of-water-on-texas-and-louisiana/?utm_term=.6ea272cbaa75
12. The Weather Channel. (2017, September 2). Historic Hurricane Harvey's recap. Retrieved from https://weather.com/storms/hurricane/news/tropical-storm-harvey-forecast-texas-louisiana-arkansas
13. Simon, J. (2017, September 10). Oil rises as U.S. refineries restart, Irma wanes. Reuters. Retrieved from https://www.reuters.com/article/us-global-oil/oil-rises-as-u-s-refineries-restart-irma-wanes-idUSKCN1BM00X
14. IHS Markit. (2017, September 12). Insight: Hurricane Harvey overview. Retrieved from https://ihs.newshq.businesswire.com/sites/ihs.newshq.businesswire.com/files/press_release/additional/Hurricane_Harvey_Overview_Report_September_12_2017.pdf
15. Associated Press. (2017, September 11). Average US gas price jumps after Harvey shuts refineries. Retrieved from https://www.cnbc.com/2017/09/11/average-us-gas-price-jumps-after-harvey-shuts-refineries.html
16. Blum, J. (2017, August 31). Harvey's toll on refineries sparks widespread gasoline shortages, price hikes. *Houston Chronicle*. Retrieved from http://www.chron.com/business/energy/article/Gasoline-shortages-in-Houston-and-beyond-are-12164762.php
17. Ivanova, I. (2017, August 31). Gas shortages in Texas as Harvey knocks out refineries. CBS News. Retrieved from https://www.cbsnews.com/news/gas-shortages-in-texas-as-harvey-knocks-out-refineries/
18. Zborowski, M. (2017, August 31). Harvey: US SPR makes emergency release; Colonial Pipeline segment shut. *Oil & Gas Journal*. Retrieved from http://www.ogj.com/articles/2017/08/harvey-us-dpr-makes-emergency-release-colonial-pipeline-segment-shut.html
19. Kumar, D.K., & Renshaw, J. (2017, August 31). U.S. fuel shortages from Harvey to hamper Labor Day travel. Reuters. Retrieved from https://www.reuters.com/article/us-storm-harvey-fuel-shortage/u-s-fuel-shortages-from-harvey-to-hamper-labor-day-travel-idUSKCN1BB3BJ
20. Matthews, C.M., & Sider, A. (2017, August 30.) Harvey ripples through U.S., global energy markets. *Wall Street Journal*. Retrieved from https://www.wsj.com/articles/harvey-ripples-through-u-s-global-energy-markets-1504137861?
21. Seba, E., & Kumar, D.K. (2017, August 31). Global fuel prices jump as Harvey's impact ripples beyond U.S. Gulf. Reuters. Retrieved from https://www.reuters.com/article/us-storm-harvey-energy/global-fuel-prices-jump-as-harveys-impact-ripples-beyond-u-s-gulf-idUSKCN1BB0FY?
22. Krauss, C., & Tabuchi, H. (2017, August 29). Harvey's toll on energy industry shows a Texas vulnerability. *New York Times*. Retrieved from https://www.nytimes.com/2017/08/29/business/energy-environment/harvey-energy-industry-texas.html
23. U.S. Department of Homeland Security. (2013, December). National Infrastructure Protection Plan (NIPP) 2013: Partnering for critical infrastructure security and resilience. Retrieved from https://www.dhs.gov/sites/default/files/publications/national-infrastructure-protection-plan-2013-508.pdf
24. Glover, J.M. (2017). Community resilience. In Homeland Defense and Security Information Analysis Center state-of-the-art report: Critical infrastructure resilience. Manuscript in preparation. Homeland Defense and Security Information Analysis Center.
25. U.S. Executive Office of the President. (2013, February 12). Presidential Policy Directive/PPD-21 – Critical Infrastructure Security and Resilience. Retrieved from https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil
26. U.S. Department of Defense. (2014, March 4). 2014 Quadrennial Defense Review. Retrieved from https://www.defense.gov/Portals/1/features/defenseReviews/QDR/2014_Quadrennial_Defense_Review.pdf
27. Dismukes, D.E. (2006, October 12–13). Interdependence of critical energy infrastructure systems. Paper presented at the Woodrow Wilson Center Cross-Border Forum on Energy Issues. Retrieved from https://www.lsu.edu/ces/presentations/2006/DISMUKES_WOODROW_WILSON_INST_1.pdf
28. Pruden, T. (2017, September 7). DLA stages 600,000 gallons of fuel at Fort Hood to support FEMA. *Fort Hood Sentinel*. Retrieved from http://www.forthoodsentinel.com/news/dla-stages-gallons-of-fuel-at-fort-hood-to-support/article_ee8f6132-9326-11e7-84eb-cb086560bbd9.html
29. Kwasinski, A. (2016, February 3). Quantitative model and metrics of electrical grids' resilience evaluated at a power distribution level. *Energies, 9*(2), 93. MDPI AG. doi:10.3390/en9020093
30. National Academies of Sciences, Engineering, and Medicine. (2017, July). Enhancing the resilience of the nation's electricity system. Washington, DC: The National Academies Press. doi:/10.17226/24836.
31. Monohan, R. (2017, August). Marine Corps' Drive to resiliency. Paper presented at the Energy Exchange Conference, U.S. Department of Energy, Tampa, Florida. Retrieved from http://www.2017energyexchange.com/wp-content/uploads/T9S5_Monohan.pdf
32. U.S. Energy Information Administration. (2017, September 20). Hurricane Irma cut power to nearly two-thirds of Florida's electricity customers. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=32992
33. Cochran, J., Denholm, P., Speer, B., & Miller, M. (2015, April). Grid integration and the carrying capacity of the U.S. grid to incorporate variable renewable energy. U.S. National Renewable Energy Laboratory. Retrieved from https://energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20Grid%20Integration%20and%20the%20Carrying%20Capacity%20of%20the%20US%20Grid%20to%20Incorporate%20Variable%20Renewable%20Energy_1.pdf
34. Congressional Budget Office. (2012, May). Energy security in the United States. Retrieved from https://www.cbo.gov/sites/default/files/112th-congress-2011-2012/reports/05-31-1colenergysecurity.pdf
35. Keim, B.D., & Muller, R.A. (2009). Hurricanes of the Gulf of Mexico. Baton Rouge: Louisiana State University Press.
36. Halff, A. (2017, August 29). From Katrina to Harvey: Storm resilience in the age of shale. Columbia University Center of Global Energy Policy. Retrieved from http://energypolicy.columbia.edu/sites/default/files/energy/From%20Katrina%20to%20Harvey_Storm%20Resilience%20in%20the%20Age%20of%20Shale.pdf
37. U.S. Energy Information Administration. (2017, January). Annual Energy Outlook 2017, Reference case table A2, Delivered Energy Consumption, All Sectors. Retrieved from https://www.eia.gov/outlooks/aeo/
38. U.S. Department of Defense. (2015, December 3). 2016 Operational Energy Strategy. Retrieved from http://www.acq.osd.mil/eie/Downloads/OE/2016%20DoD%20Operational%20Energy%20Strategy%20WEBc.pdf
39. Brodwin, E. (2017, September 12). A new analysis suggests Hurricane Harvey caused 4.6 million pounds of chemicals to be released — but the risk is still unclear. Business Insider. Retrieved from http://www.businessinsider.com/oil-refineries-hit-harvey-releasing-chemicals-pollutants-2017-8
40. U.S. Department of Energy. (2016, August). Long-Term Strategic Review (LTSR) of the U.S. Strategic Petroleum Reserve (SPR) Report to Congress. Retrieved from https://energy.gov/fe/downloads/long-term-strategic-review-ltsr-us-strategic-petroleum-reserve-spr-report-congress
41. Blum, J. (2017, September 8). Harvey, Irma show value of Strategic Petroleum Reserve, energy experts say. *Houston Chronicle*. Retrieved from http://m.chron.com/business/

energy/article/Bush-energy-adviser-Harvey-Irma-show-value-of-12183557.php?cmpid=twitter-mobile
42. Muckerman, T., & Priestley, S. (2017, September 10). Phillips 66 Is tapping the Strategic Petroleum Reserve. What's the Impact? The Motley Fool. Retrieved from https://www.fool.com/investing/2017/09/10/phillips-66-is-tapping-the-strategic-petroleum-res.aspx
43. Katakey, R. (2017, September 1). Gasoline falls as refineries shut by Harvey prepare to reopen. *Houston Chronicle*. Retrieved from http://www.chron.com/business/energy/article/Gasoline-Gain-and-Oil-Pain-Spurred-by-Storm-as-12166771.php
44. Oil & Gas Journal. (2017, September 12). EIA: Post-storm timeline uncertain for full return of US oil production, refining. Retrieved from http://www.ogj.com/articles/2017/09/eia-post-storm-timeline-uncertain-for-full-return-of-us-oil-production-refining.html
45. U.S. Energy Information Administration. (2017, September 20). Weekly Petroleum Status Report, Data for week ended: September 15, 2017. Retrieved from https://www.eia.gov/petroleum/supply/weekly/pdf/wpsrall.pdf
46. Smith, I. (2014, Spring). When disaster strikes. Energy Source. Fort Belvoir, VA: Defense Logistics Agency. Retrieved from http://www.dla.mil/Portals/104/Documents/Energy/Energy%20Source/E_2014AprilEnergySource_140401.pdf
47. INTEK, Inc. (2014, September). United States fuel resiliency, Volume II: U.S. fuels supply infrastructure vulnerability to natural and physical threats. Washington, D.C.: U.S. Department of Energy. Retrieved from https://energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20United%20States%20Fuel%20Resiliency%20Volume%20II.pdf
48. U.S. National Institute of Standards and Technology. (2006, June). Performance of physical structures in Hurricane Katrina and Hurricane Rita: A reconnaissance report. Retrieved from http://fire.nist.gov/bfrlpubs/build06/PDF/b06016.pdf
49. U.S. Department of Energy. (2010, August). Hardening and resiliency: U.S. energy industry response to recent hurricane seasons. Retrieved from https://www.oe.netl.doe.gov/docs/HR-Report-final-081710.pdf
50. Harder, A. (2017, September 1). Axios Generate Newsletter. Retrieved from https://www.axios.com/generate-2480069194.html
51. Bisen, L.S., & Singh, D.K. (2016, August). Mobile transformers and mobile substations for rapidly restoring electrical service. *Journal of Emerging Technologies and Innovative Research, 3(8)*. Retrieved from http://www.jetir.org/papers/JETIR1608015.pdf
52. Crane, K., Knopman, D., Burger, N., Narayanan, A., Powers, J.D., & Willis, H.H. (2016, September). Scenario development for the 2015 Quadrennial Energy Review: Assessing stresses, opportunities, and resilience in the transmission, storage, and distribution systems for oil, and refined-oil products, electricity, and natural gas. RAND Corporation. Retrieved from https://energy.gov/sites/prod/files/2016/09/f33/Rand%20Corporation%20Doc.pdf
53. INTEK, Inc. (2014, September). United States fuel resiliency, Volume III: U.S. fuels supply infrastructure vulnerability to natural and physical threats. Washington, D.C.: U.S. Department of Energy. Retrieved from https://energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20United%20States%20Fuel%20Resiliency%20Volume%20II.pdf
54. U.S. Department of Energy. (2014, May 2). Energy Department announces first regional gasoline reserve to strengthen fuel resiliency. Retrieved from https://energy.gov/articles/energy-department-announces-first-regional-gasoline-reserve-strengthen-fuel-resiliency
55. Quadrennial Energy Review (QER) Task Force. (2015, April 21). Quadrennial Energy Review: Energy transmission, storage, and distribution infrastructure, Appendix A: Liquid fuels. Retrieved from https://energy.gov/sites/prod/files/2015/09/f26/QER_AppendixA_LiquidFuels_0.pdf
56. U.S. Department of Energy. (2017). Creating the Northeast Gasoline Supply Reserve. Retrieved from https://energy.gov/NODE/1041666
56. U.S. Department of Energy. (2017). Northeast Home Heating Oil Reserve (NEHHOR). Retrieved from https://energy.gov/fe/services/petroleum-reserves/heating-oil-reserve
57. Stoeckmann, E. (2015, November 5). DLA Energy partners with DOE's emergency petroleum stockpiles. Defense Logistics Agency Energy Public Affairs. Retrieved from http://www.dla.mil/Energy/About/News/Article/627830/dla-energy-partners-with-does-emergency-petroleum-stockpiles/
58. Musharah, A.H., Al-Nasser, A.N., Al-Kaltham, A.A., & Ely, T.L. (2010, April 19). Saudi Aramco studies long-term storage effects on FCCU gasolines. *Oil & Gas Journal*. Retrieved from http://www.ogj.com/articles/print/volume-108/issue-14/technology/saudi-aramco-studies.html
59. Jeon, C.H., Park, C.K., Na, B.K., & Kim, J.K. (2017, September 1). Properties of gasoline stored in various containers. *Energies, 10*(9), 1307. MDPI AG. doi:10.3390/en10091307
60. Johnson, D.F. (2009, May 12). Developing refined products storage in the Strategic Petroleum Reserve: Statement of David F. Johnson, Deputy Assistant Secretary for Petroleum Reserves before the Committee on Energy and Natural Resources, United States Senate. Washington, D.C.: Department of Energy. Retrieved from https://energy.gov/fe/articles/developing-refined-products-storage-strategic-petroleum-reserve
61. Ford, A. (2005). Simulating the impacts of a strategic fuels reserve in California. *Energy Policy, 33*, 483–498. doi:10.1016/j.enpol.2003.08.013
62. Biernat, K., Ed. (2015, February 4). Storage stability of fuels. Rijeka, CR: InTech. Retrieved from https://www.intechopen.com/books/storage-stability-of-fuels
63. Nichols, G., Haupt, S.E., Gagne, D.J., Rucci, A., Toumey, C., Deshpande, G., Lanka, P., & Youngblood, S. (2017). Homeland Defense and Security Information Analysis Center state-of-the-art report: Artificial intelligence and machine learning for defense applications. Manuscript in preparation. Homeland Defense and Security Information Analysis Center.
64. Wilson, M.L., Corbet, T.F., Baker, A.B., & O'Rourke, J.M. (2015, April). Simulating impacts of disruptions to liquid fuels infrastructure. Sandia National Laboratories. Retrieved from https://energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20Simulating%20Impacts%20of%20Disruptions%20to%20Liquid%20Fuels%20Infrastructure.pdf
65. Bournes, T. (2017, Summer). DLA Energy, University of Arkansas partnership creates fuel supply network simulation, software. Energy Source. Fort Belvoir, VA: Defense Logistics Agency. Retrieved from http://www.dla.mil/Portals/104/Documents/Energy/Energy%20Source/Current%20Edition/E_EnergySource_Summer2017.pdf
66. Summers, J. (2017, September 19). Oil jumps as fuel draw adds to talk of more OPEC cuts. Bloomberg. Retrieved from https://www.bloomberg.com/news/articles/2017-09-19/oil-advances-on-signs-u-s-stockpile-gains-eased-after-harvey
67. U.S. Energy Information Administration. (2017, September 27). Weekly Petroleum Status Report. Retrieved from https://www.eia.gov/petroleum/supply/weekly/pdf/wpsrall.pdf
68. Halper, E. (2017, September 12). An exasperating hunt for gasoline in Florida as Hurricane Irma's evacuees scramble to come home. *Los Angeles Times*. Retrieved from http://www.latimes.com/nation/la-na-florida-irma-gasoline-20170912-story.html?
69. Orlando Sentinel. (2017, September 19). Florida may set up gasoline reserve for hurricanes. Retrieved from http://www.orlandosentinel.com/news/politics/political-pulse/os-hurricane-irma-corcoran-committee-20170919-story.html
70. Page, P., & Hughes, S. (2017, September 26). Puerto Rico port reopens but relief distribution remains slow. *Wall Street Journal*. Retrieved from https://www.wsj.com/articles/puerto-rico-port-reopens-but-relief-distribution-remains-slow-1506446137
71. Respaut, R., Graham, D., & Resnick-Ault, J. (2017, September 27). For desperate Puerto Ricans, fuel a precious commodity. Reuters. Retrieved from http://www.reuters.com/article/us-usa-puertorico-fuel/for-desperate-puerto-ricans-fuel-a-precious-commodity-idUSKCN1C216B
72. Geman, B. (2017, September 26). Axios Generate Newsletter. Retrieved from https://www.axios.com/generate-2489407280.html
73. U.S. Department of Homeland Security, & U.S. Department of Energy. (2007, May). *Energy: Critical Infrastructure and Key Resources Sector-Specific Plan as input to the National Infrastructure Protection Plan (Redacted)* (Rep.). Retrieved from https://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/Energy_SSP_Public.pdf

Joel Hewett
Subject Matter Expert, Homeland Defense and Security Information Analysis Center

Joel Hewett joined the Homeland Defense & Security Information Analysis Center (HDIAC) in 2017, where he applies a decade of experience in energy technology issues as a subject matter expert. He holds an M.S. from the Georgia Institute of Technology, in the history and sociology of technology and science, where he was the inaugural Melvin Kranzberg fellow. He also holds an A.B. in literature from Davidson College, where he was a John Montgomery Belk scholar. His book-length study of the offshore oil and gas program in the U.S., *The Secret of the Sea*, will be published by the Interior Department in 2017.



4-D Printing:

Devin J. Roach
Craig M. Hamel
Jiangtao Wu
Xiao Kuang, Ph.D.
Martin L. Dunn, Ph.D.
&
H. Jerry Qi, Ph.D.

Introduction

With the advent of 3-D printing, structurally complex objects that were once unbuildable can now be easily manufactured. However, what if these objects could be designed and manufactured to respond or change in predictable or pre-programmed ways to a stimulus applied after their production? Enter 4-D printing.

The term "4-D printing" was coined in February 2013 [1]. The first academic paper to address the concept appeared seven months later [2], describing how 3-D printing techniques can combine with active or smartmaterials to form 4-D printed objects whose shape, properties, and functionalities can be deliberately changed after printing [3,4]. 3-D printing is a process of rapidly creating three-dimensional objects in a layer-by-layer fashion. Today, many different technologies exist to implement 3-D printing, including powder bed laser melting (where material powders are melted by a raster laser to form a layer of solid material with a well-defined geometry) and vat photopolymerization, which takes a layer of polymer resin and converts it to a layer of solid by a raster laser or a projector. Figure 1 depicts another method, polyjet 3-D printing technology, which is used by researchers in the Mechanics of Soft Materials Laboratory at Georgia Institute of Technology (Georgia Tech). In this method, several inkjet print heads are used to jet different polymer resins (in a manner similar to how different color inks are jetted onto paper in an inkjet printer), after which the resin is cured (or solidified) using ultraviolet light.

In traditional 3-D printing, an object is formed with a fixed shape, and that shape is not intended to change. 4-D printing enables a 3-D printed object to change its shape or form well after the printing process has been completed via exposure to a specific trigger stimulus. Researchers typically rely on environmental free energies such as moisture [5,6], temperature [7-10], light [11-13], or a combination of these [14-16] to provide the stimulus for the activation of a 4-D printed object. Non-free energies like a specific electrical current or chemical stimuli have also been used to activate a 4-D object [17,18]. The use of a highly specific (or proprietary) triggering energy could be used to prevent unauthorized use or activation of a 4-D object. It should be noted that just as the concept of 3-D printing now encompasses many different implementation methods, some of which do not directly involve jet-based printing, 4-D printing is a similarly broad concept. Most of all, however, the 4-D printing concept is defined by its emphasis on the time evolution factor or shape change of an object, rather than the details of the technologies or methods used to achieve shape change.

4-D printing is typically achieved through multi-material (m^2) 3-D printing techniques in which different materials can be precisely placed in space. The most common method used in m^2 3-D printing is the polyjet method [19] (see Figure 1). The direct-write method is another common technique [20]. 4-D printing typically uses two or more materials, at least one of which is active and can respond to a trigger stimulus. Active, or smart materials, include a wide variety of substances that can change their appearance, material properties, and/or shape in a controlled manner in response to an external stimulus. Here, "active" or "smart" refers

Image Credit | *Inside a massive 3D printer a delicate head moves at lightning speed to precisely deposit heated plastic layer-by-layer to create a hardened part. Photo Illus- ting_edge_3d_printers).*

Potential Applications of 3-D Printed Active Composite Materials

to the fact that these materials can “sense” their environment, so to speak, reacting to changes in environmental conditions such as temperature and/or humidity change or ultraviolet irradiation. Based on the type and intensity of the trigger stimulus, smart materials can change their physical state, such as deforming from the shape in which the material was manufactured into a different shape—one programmed in advance by a human operator.

To date, two types of active materials are under investigation for use in 4-D printing: shape memory polymers (SMPs) and hydrogels. SMPs are used in 3-D printing layered composite structures—also known as printed active composites (PACs)—that contain multiple families of shape memory polymer fibers [2]. Through proper design of the distributions of SMP fibers in the non-SMP matrix, many interesting shape changing properties can be achieved [7,21]. Hydrogels that swell in water or in solution can also be used to produce shape change when used alongside a non-swelling polymer, which converts the swelling force into a biased mechanics field [14,22]. Research into 4-D printing applications has already accomplished one-way activation in an object from an initial, programmed state, into a permanent final state [2]. Subsequent research has allowed for the programming of multiple activation states within a single composite structure [19], and only in the past year have we begun to achieve fully-reversible two-way actuation [17].

These capabilities, combined with the typical advantages offered by 3-D printing (such as agile manufacturing), make 4-D printing a potential future solution for many Department of Defense (DoD) applications that must confront unpredictable conditions and can be strictly constrained by space, logistics, and limited resources (e.g., electrical power). For example, 4-D printing can aid in the fabrication of sensors with multiple stimulus-responsive groups, able to notify warfighters to changing ambient conditions or the presence of an imminent danger [23], active truss structures capable of gigantic shape change that can be used as free-standing, self-assembling tents or as platforms for 4-D electromagnetic devices (like morphing antennae) [24], or soft micro-robots that can be fabricated for therapeutic drug delivery to a specific location [25,26].

There are numerous opportunities for fabricating smart structures through 4-D printing. In this article, we discuss several projects recently completed by our research group at the Georgia Tech and a team of collaborators, starting with the use of SMPs in printed active composites that require thermomechanical programming to induce shape change. We then discuss how internal stress-induced shape changes can be used in 4-D printing, and how objects can transform directly off the print bed. Finally, recent progress with the use of hydrogels as active materials is examined. In each section we use these projects to illustrate the immense potential that 4-D printing has for a wide array of DoD applications.

Printed Active Composites

As discussed above, 3-D printing allows for the placement or fusion of different materials into one object to form a composite. When one material is an active material, the composite largely inherits the “smart” nature of the active material, while the specific parameters of those active motions in the composite object are determined by how the active and non-active materials interact; this offers 4-D printed objects a high amount of tunability [8,19,27].

Polyjet printing technology allows for printing SMPs with different glass transition or

tration created by HDIAC and adapted from RDECOM photo by David McNally (available for viewing at: https://www.army.mil/article/88464/army_researchers_use_cut-

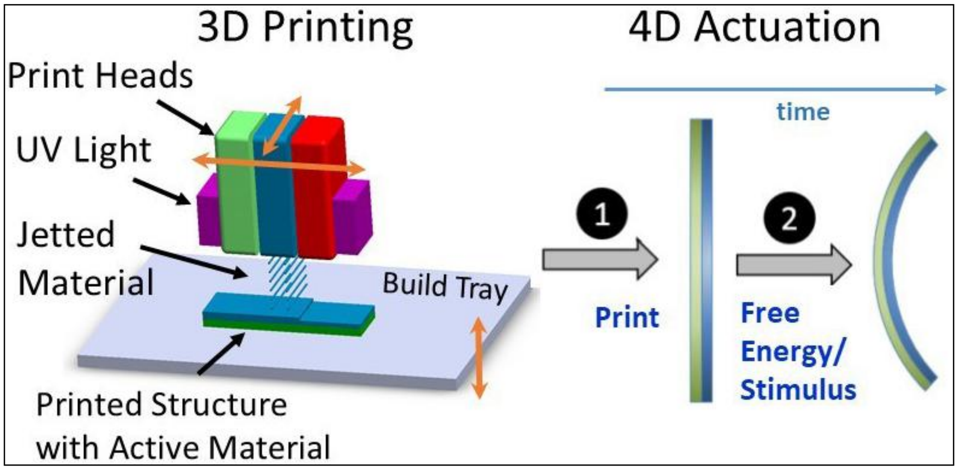


Figure 1: Illustration of actuation of a 4-D printed object upon stimulus after a standard (polyjet) 3-D printing process. Adapted from [10].

activation temperatures, and thus can be used to create active components [21]. An SMP is a polymer that can be programmed (or formed) into a temporary shape and later made to recover its permanent shape upon exposure to its trigger stimulus [28]. To date, temperature is the most commonly used trigger stimulus in SMP-focused studies. In a typical application, the SMP can be programmed into a shape through a thermomechanical loading process in which the SMP is first heated to above its transition temperature (such as glass transition), deformed, and then cooled. Upon unloading at the low temperature, the SMP remains in the temporary, deformed shape. To recover its permanent shape, the SMP is heated to a temperature above the transition temperature. It should be noted that the shape change from temporary to permanent in this example is a one-time event (i.e., the SMP would have to be programmed again by the thermomechanical deformation). However, there are research efforts underway to make multi-use reversible shape changes possible [29,30].

Figure 2A depicts an example of a printed active composite using an SMP that results in bending. This PAC laminate consisted of a single layer of SMP fibers in a soft matrix. After printing, the PAC was programmed with a simple thermal-mechanical programming step (including stretching at a high temperature, cooling to a low temperature (0 C), and releasing the mechanical load), and the PAC object was bent. The resulting bending can be used to create active origami structures such as the self-folding airplane shown in Figure 2B. The 4-D printed active origami structures demonstrated their ability to solve engineering issues related to the packing of large structures into small volumes, for purposes related to storage and transportation. Additionally, this folding/assembling process that was triggered by a stimulus and executed automatically (self-folding or self-assembling) has the advantage of being able to overcome the limitation of requiring manpower to work in extreme environments or urgent/dangerous situations. For example, a printed flat pack structure could deploy into a three-dimensional structure by applying the trigger stimulus, producing, for example, a self-foldable building or tent for immediate use in the field [24]. For another example, the hydrogel-based shape-shifting structures can be used as a rain-expandable structure requiring minimal human involvement to utilize [31].

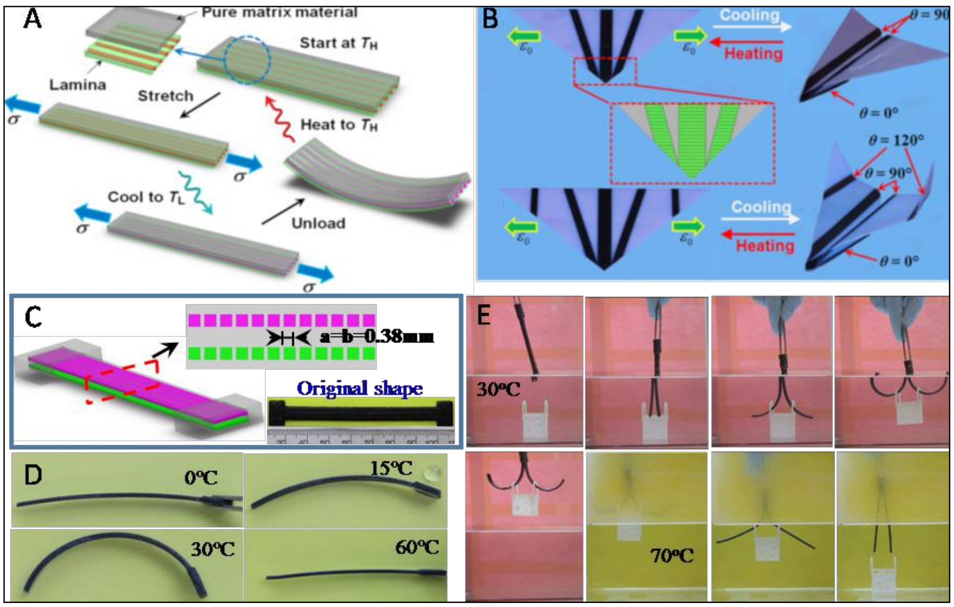


Figure 2: 4-D printing of SMP composites. (A) Schematic of the design, programming step, and shape memory cycle of a single-layer fiber-matrix composite [2]. (B) Active origami airplane utilizing the active hinges [33]. (Released) (C) The design of the composite structure with two layers of different SMP fibers embedded inside the rubbery matrix. (D) The shape changing behavior of the printed and programmed composite at different temperatures. (E) A smart hook application of the SMP composite.

Wu, et al. [19] took the PAC method one step further in 2015 by incorporating multiple SMP fibers into a 4-D printed object, as shown in Figure 2C. The two fiber types had different activation temperatures, at around 37 C and 57 C. After printing, the PAC was programmed with a simple thermal-mechanical programming step as described above. After programmed, the PAC could "memorize" two temporary shapes and would recover to the flat, permanent shape when stimulated by heat. Figure 2D shows the shapes of the PAC activated at different temperatures.

Many interesting applications for active structures could be realized using PACs. Figure 2E shows an active hook: the flat hook could morph into semi-circular shapes when immersed in 30 C water and lift a small box. Subsequently, upon immersion in 70 C water, the hook returned to a straight shape, releasing the box. The capability of changing shape from one to another under moderate temperature change and then returning to the initial shape under a higher temperature offers a significant advantage in many DoD applications. For example, such a design could be used as a suture to tighten wounds or as a fixture to attach devices under relatively moderate temperature in the battlefield; once the warfighter or the devices return to the hospital or service center, a higher temperature can be applied to quickly release the fixture [32]. In addition, such a design could be used for soft robotics, where a robot made of soft materials can change its configuration dramatically to meet different application requirements. By using the multiple-shape or dual-programmed PAC, the temporary intermediate shape could be used for the soft robots to pass obstacles, like a barricade or small opening, before recovering to its original shape for use in its final location.

PACs do have some limitations. For example, the PACs illustrated in Figure 2 are successful in creating active structures; however, they require extensive programming using the multiple-step thermal-mechanical process (including heating, deforming, cooling, and removing load) before actuation. In addition, the actuation is single-use; achieving reversible or two-way shape change would require special designs or mechanisms.

Direct 4-D Printing Using Printed Active Composites

Recently, our research group and collaborators developed a new method such that a composite can be directly activated and made to maintain a new shape through simple heating [10]. Here, we utilized the residual strain induced during 3-D printing, which was controlled by the material composition and printing process parameters. When a laminated strip with an SMP in conjunction with an elastomer was printed (the printing method is similar to the one used in the PAC discussed above), the elastomer was imbued with the residual strain created by the 3-D printing process. After it was removed from the printing tray and heated, the laminate object bent due to the residual strain and the thermal expansion mismatch of the two materials (see Figure 3A). This new bent shape is permanent; the strip would not change upon further cooling and heating after it was first bent.

This simple bending process could be used to create more complex shape changes, such as the expanding lattice shown in Figure 3B or the shrinking lattice shown in Figure 3C. The difference between Figure 3B and Figure 3C lies in where the elastomers are placed, which indicates the large degree of design freedom that 3-D printing offers. Figure 3D depicts a 4-D printed object that was designed to be printed flat but raises up and expands to form a dome upon heating. In Figure 3E, initially flat petals bend and form a closing flower.

As discussed above, in this direct 4-D printing method, the shape assumed after heating is permanent. An obvious advantage of this new method is the decreased cost in supporting materials and printing time. For example, for the dome structure, conventional 3-D printing requires a supporting material underneath the dome, which also takes additional time to print. We estimate that 4-D printing can save approximately 70 percent of materials and time for a dome or similar structure formed with thin lattices. In addition, this new method is very simple to implement and could be used for a wide range of DoD applications. For example, the lattice structures illustrated in Figures 3B and 3C can potentially be used as quickly expandable fencing or as metamaterials with tunable bandgap for acoustic applications.

Internal Shrinkage, Stress-Induced Shape Change

Volume shrinkage is a common event when a polymer is cured (changed from a liquid resin to a solid polymer); therefore, it occurs in many 3-D printing processes, especially when photopolymerization is used. Volume shrinkage in general should be avoided in 3-D printing techniques, as it can cause shape distortion if the geometry of the printed part is especially complex. However, if such a volume change can be precisely controlled, its occurrence can be advantageous for creating shape-changing structures [11,34].

Our research group developed a simple method to fabricate thin film structures by utilizing the volume shrinkage stress induced during the photopolymerization process [35] (see Figure 4A). A commercial projector was used as the light source. Photoabsorbers were added into the resin to attenuate the light, creating a light intensity gradient across the thickness direction within the liquid resin. Therefore, the material directly exposed to the light (the bottom of the resin shown in Figure 4A) was cured faster than the material further from the light, resulting in a nonuniform volume shrinkage and stress gradient in the cured polymer. Once the material was removed from the

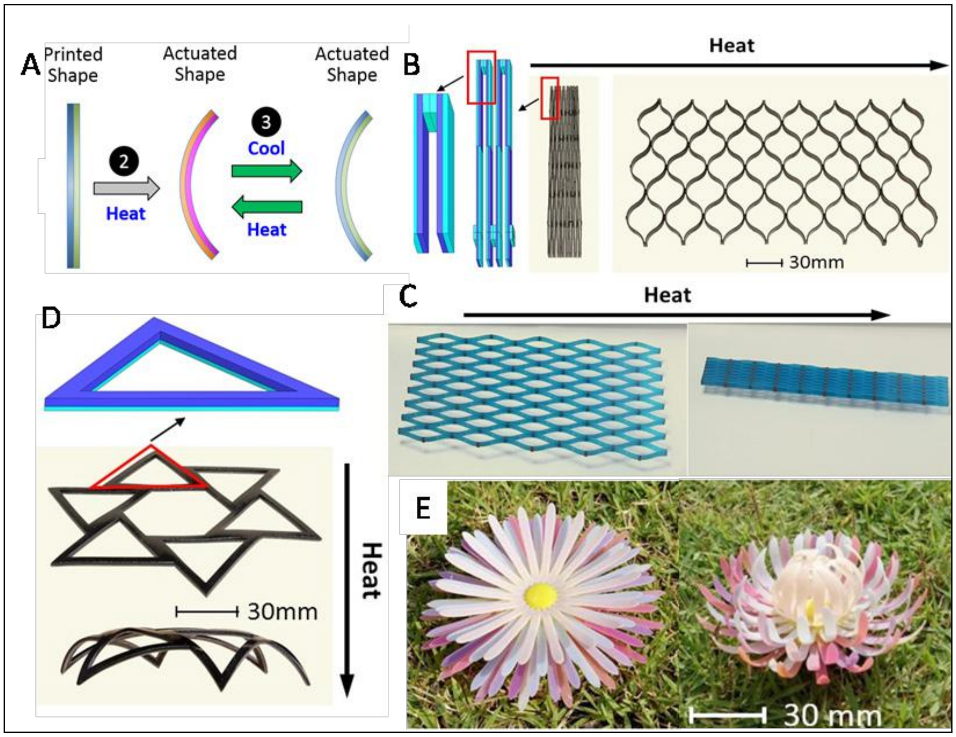


Figure 3: (A) The concept of direct 4-D printing where two layers of different materials are printed together, and the difference of the thermal expansion coefficients and the printing-induced internal strain can induce shape changing behavior (B) A lattice structure that expands greatly upon heating (C) A lattice that can shrink upon exposure to heat (D) A flat structure that can expand upon heating to create a dome structure (E) Printed flower blooms into a configuration where petals at different layers assume final configurations with different curvatures. Adapted from [10].

curing stage, the cured polymer sheet was activated and bent toward the less cured portion (the top surface in Figure 4A).

Further experiments demonstrated that the bending curvature depended on the illumination energy, which can be controlled by the intensity of the light, the length of illumination, or both (see Figure 4B). The light intensity was related to the grayscale in the CAD drawing; as a result, by precisely controlling the spatial distribution of the designed grayscale pattern, we easily created complex 3-D origami structures. Figure 4C illustrates a flat polymer sheet after photopolymerization (using the pattern in the inset), and Figure 4D illustrates the bending shape achieved after removal from the printing stage. Complex polyhedron structures may also be fabricated, as illustrated in Figures 4E and 4F.

To extend the application of this method, a two-sided illumination procedure was proposed, as illustrated in Figure 4G. After the first illumination step, the material was flipped, and a second gray level pattern was projected. Using this method, origami structures that require bending deformation toward different directions can be printed (see Figure 4H). One advantage of this method is that it can quickly produce 3-D printed, thin film structures by using a commercial projector. One potential application is to fabricate contact lenses, as illustrated in Figure 4I. It should be noted that this method creates shape changes that are currently irreversible and single-use only. Recently, we extended this method to program reversible shape changes into objects by tuning the materials used in this approach [11].

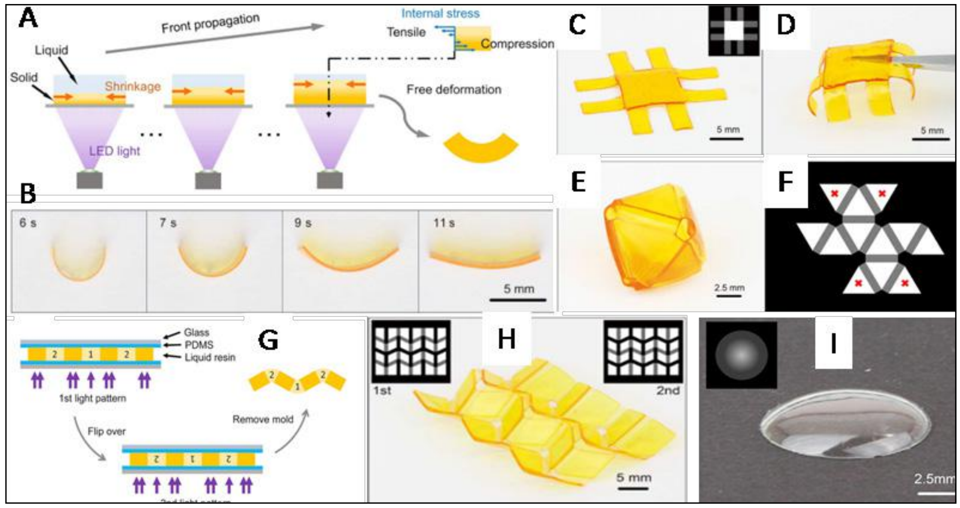


Figure 4: (A) Schematic of volume shrinkage–induced bending (B) The bending deformation of the samples controlled by the irradiation times (C) Polymer sheet directly after photopolymerization (D) Free bending shape of (C). (E)-(F) A polyhedron created by one-side illumination using light pattern shown in (F). (G) Using two-side illuminations to fabricate more complex origami structures (schematic). (H) Origami structure created by the two-side illumination method. (I) Contact lens fabricated using a commercial projector as the light exposure source.

Hydrogel for 4-D Printing of Reversible Shape Changing Structures

Some highly absorbent materials, such as hydrogels, yield large volume changes upon introduction to solvents in a process called swelling. The swelling and de-swelling behavior of hydrogels can be used to force shape change in 4-D printed structures [5,7,20]. However, one disadvantage of hydrogels is their softness, with Young's modulus in the range of a few tens to hundreds of kPas (although their bulk modulus could be very high).

In 2015, our research group developed a new design that utilized the swelling of a hydrogel as the driving force and the temperature dependent modulus change of a SMP as a switch to create shape change components capable of being stiff in two different configurations [7]. Figure 5A illustrates a design in which the hydrogel was sandwiched between an SMP layer and an elastomer layer. The elastomer was also deposited in columns to convert the hydrogel's swelling to in-plane expansion. Figure 5B illustrates the deformation process.

The hydrogel sample was first printed according to the design in Figure 5A. It was then immersed in cold water (~0 C) for ~12 hours (see S1 in Figure 5B), allowing the hydrogel to absorb water. Because the temperature was low, the SMP had a very high modulus, which prevented the strip from deforming. The strip was then moved to a hot water bath (see S2 in Figure 5B). The modulus of the SMP strongly depended on temperature. Because of the temperature rise, the modulus of the SMP dropped by approximately three orders of magnitude, which led to a quick bending of the strip (typically within 10–20 seconds). The strip was removed from the hot water bath (see S3 in Figure 5B), and it remained in the bent shape. The strip was then left to dry in a low temperature environment (see S4 in Figure 5B). The resulting dehydrated strip was stiff—able to support a load of 25 grams. When the strip was heated again, it returned to its straight, unbent shape.

Figure 6: This image is one in a series of images showing the transformation of a 4-D-printed hydrogel composite structure after its submersion in water. (Source: National Science Foundation)

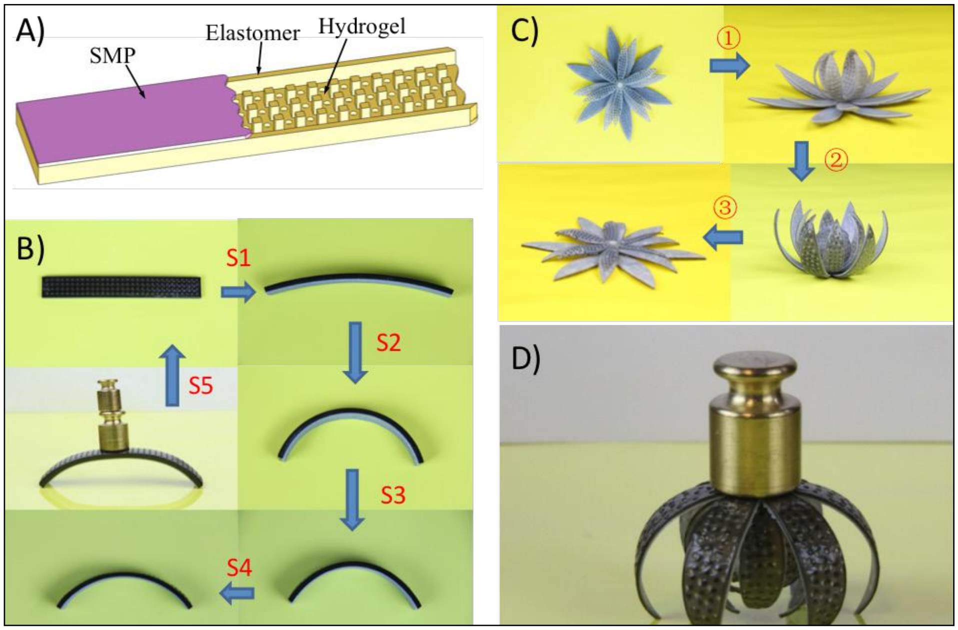


Figure 5: Hydrogel based design for 4-D printing applications. (A) The schematic graph of the design concept where the hydrogel is sandwiched between an SMP layer and an elastomer layer. The elastomer is also used in columns to convert the volume deformation of hydrogel swelling to in-plane expansion. (B) The experimental process showing the deformation. The deformed structure is stiff and can carry a 25g load. (C) The design can be used for a flower (D), which can be very stiff to carry a 25g load.

This process could easily be used in more complicated designs. For example, our research team also printed a flower design (see Figure 5C). The flower closed its petals once immersed in cold water. The flower also carried a load of 25 grams at low temperature (see Figure 5D). This new design was capable of reversible shape changes, fast deployment speeds (within ~10 seconds), and a high degree of stiffness. This makes it a good candidate for DoD applications, such as for use in micro unmanned aerial vehicles (UAVs) or small UAVs (SUAVs) for surveillance. For example, the aforementioned steps (see S1–S4 in Figure 5B) could be performed on an SUAV promptly after fabrication. The SUAV could then be deployed into a flying configuration once activated by temperature (set either to an environment change or through remotely controlled electrical heating).

Future Possibilities

The field of 4-D printing is rapidly developing. It enables the targeted evolution of a 3-D printed structure's shape, property, and functionality over time through the use of printable active materials. This article discussed several recently developed and facilely approached methods from our research group and collaborators, including shape-memory polymer-based unconstrained-thermo-mechanics; internal stress-based constrained-thermo-mechanics; and hydrogel-based hydro-mechanics. The use of active materials, realized through 3-D printing, enables innovative applications previously unachievable by conventional manufacturing processes. For example, potential military applications for 4-D printed hydrogel structures could be pursued in key areas including, but not limited to, improved battlefield medical devices for wound healing [36,37], drug delivery systems [38], wearable electronics [39], and energy-storing supercapacitors [40].

However, as with any emerging field of research and development, 4-D printing still faces many challenges. Each class of potential applications presents a different set of requirements that the material system must satisfy. For instance, biomedical devices must be fabricated from a bio-compatible polymer so that they may be introduced into the body without triggering harmful response [41,42]. Similarly, a major roadblock in the widespread implementation of flexible, wearable electronics is the lack of a proper energy storage system that can withstand constant mechanical deformation from the wearer's movement [43]. Another challenge associated with 4-D printing is that most printing processes deploy thin structures in order to produce a large shape change relative to their size. Although thin structures are routinely pursued in DoD applications for lightweight equipment, it will also be important to achieve shape change

Figure 7: This is an example of a mini-UAV. This mini-UAV was developed based on a decade of research conducted by Army Research Laboratory as well as partners in academia and industry. (Source: Army Research Laboratory)

in large, thicker structures for more durable applications. Therefore, it is necessary for the 4-D printing processes discussed in this article to be closely tailored to a given structure's end-use applications and environmental requirements.

The potential benefits of using applications of 4-D objects go well beyond the feature of simple shape-shifting. Other stimulus-responsive properties, such as self-healing and self-sensing, are beginning to be incorporated into 4-D printed structures [44-46]. Further types of application may be brought to fruition if this technology is implemented with other advances, such as color-shifting textiles intended to help warfighters conceal themselves by bending the light reflected from the clothing [47].

To better implement and maximize the potential applications of 4-D printing, further research should be aimed at developing novel, stronger, and more durable printable active materials, and producing new 4-D printing concepts and predictive design tools based on theory. With these efforts, 4-D printing may become beneficial for many future DoD applications. ■

Acknowledgment

The authors are grateful for the financial support from the Air Force Office of Scientific Research (FA9550-13-1-0088 (expired in 2016), FA9550-16-1-0169; Dr. B.-L. "Les" Lee, Program Manager) and a DURIP grant from AFOSR (FA9550-16-1-0160; Dr. B.-L. "Les" Lee, Program Manager), and from the National Science Foundation (grant CMMI-1462895, CMMI-1462894).

References

1. Tibbits, S. (2013, February). The emergence of "4D printing" [Video]. Presented at TED2013. Video retrieved from https://www.ted.com/talks/skylar_tibbits_the_emergence_of_4d_printing
2. Ge, Q., Qi, H. J., & Dunn, M. L. (2013). Active materials by four-dimension printing. *Applied Physics Letters, 103*(13), 131901. doi:10.1063/1.4819837
3. Tibbits, S. (2014). 4D printing: Multi-material shape change. *Architectural Design, 84*(1), 116-121. doi:10.1002/ad.1710
4. Pei, E. (2014). 4D printing: Dawn of an emerging technology cycle. *Assembly Automation, 34*(4), 310-314. doi:10.1108/aa-07-2014-062
5. Raviv, D., Zhao, W., Mcknelly, C., Papadopoulou, A., Kadambi, A., Shi, B., . . . Tibbits, S. (2014). Active printed materials for complex self-evolving deformations. *Scientific Reports, 4*(1). doi:10.1038/srep07422
6. Jamal, M., Kadam, S. S., Xiao, R., Jivan, F., Onn, T., Fernandes, R., . . . Gracias, D. H. (2013). Bio-origami hydrogel scaffolds composed of photocrosslinked PEG bilayers. *Advanced Healthcare Materials, 2*(8), 1142-1150. doi:10.1002/adhm.201200458
7. Mao, Y., Yu, K., Isakov, M. S., Wu, J., Dunn, M. L., & Qi, H. J. (2015). Sequential self-folding structures by 3D printed digital shape memory polymers. *Scientific Reports, 5*(1). doi:10.1038/srep13616.
8. Yu, K., Dunn, M. L., & Qi, H. J. (2015). Digital manufacture of shape changing components. *Extreme Mechanics Letters, 4*, 9-17. doi:10.1016/j.eml.2015.07.005
9. Zhang, Q., Zhang, K., & Hu, G. (2016). Smart three-dimensional lightweight structure triggered from a thin composite sheet via 3D printing technique. *Scientific Reports, 6*(1). doi:10.1038/srep22431
10. Ding, Z., Yuan, C., Peng, X., Wang, T., Qi, H. J., & Dunn, M. L. (2017). Direct 4D printing via active composite materials. *Science Advances, 3*(4). doi:10.1126/sciadv.1602890
11. Zhao, Z., Wu, J., Mu, X., Chen, H., Qi, H. J., & Fang, D. (2016). Desolvation induced origami of photocurable polymers by digit light processing. *Macromolecular Rapid Communications,38*(13), 1600625. doi:10.1002/marc.201600625
12. Zhao, Z., Wu, J., Mu, X., Chen, H., Qi, H. J., & Fang, D. (2017). Origami by frontal photopolymerization. *Science Advances, 3*(4). doi:10.1126/sciadv.1602326
13. Laflin, K. E., Morris, C. J., Muqeem, T., & Gracias, D. H. (2012). Laser triggered sequential folding of microstructures. *Applied Physics Letters, 101*(13), 131901. doi:10.1063/1.4754607
14. Gladman, A. S., Matsumoto, E. A., Nuzzo, R. G., Mahadevan, L., & Lewis, J. A. (2016). Biomimetic 4D printing. *Nature Materials, 15*(4), 413-418. doi:10.1038/nmat4544
15. Bakarich, S. E., Gorkin, R., Panhuis, M. I., & Spinks, G. M. (2015). 4D printing with mechanically robust, thermally actuating hydrogels. *Macromolecular Rapid Communications, 36*(12), 1211-1217. doi:10.1002/marc.201500079
16. Kuksenok, O., & Balazs, A.C. (2016). Stimuli-responsive behavior of composites integrating thermo-responsive gels with photo-responsive fibers. *Materials Horizons, 3*(1), 53-62.
17. Yuan, C., Roach, D. J., Dunn, C. K., Mu, Q., Kuang, X., Yakacki, C. M., . . . Qi, H. J. (2017). 3D printed reversible shape changing soft actuators assisted by liquid crystal elastomers. *Soft Matter, 13*(33), 5558-5568. doi:10.1039/c7sm00759k
18. Naficy, S., Gately, R., Gorkin, R., Xin, H., & Spinks, G. M. (2016). 4D printing of reversible shape morphing hydrogel structures. *Macromolecular Materials and Engineering, 302*(1), 1600212. doi:10.1002/mame.201600212
19. Wu, J., Yuan, C., Ding, Z., Isakov, M., Mao, Y., Wang, T., . . . Qi, H. J. (2016). Multi-shape active composites by 3D printing of digital shape memory polymers. *Scientific Reports, 6*(1). doi:10.1038/srep24224
20. Lewis, J.A. (2006). Direct ink writing of 3D functional materials. *Advanced Functional Materials,16*(17), 2193-2204. doi:10.1002/adfm.200600434
21. Yu, K., Ritchie, A., Mao, Y., Dunn, M. L., & Qi, H. J. (2015). Controlled sequential shape changing components by 3D printing of shape memory polymer multimaterials. *Procedia IUTAM, 12*, 193-203. doi:10.1016/j.piutam.2014.12.021
22. Thérien-Aubin, H., Wu, Z. L., Nie, Z., & Kumacheva, E. (2013). Multiple shape transformations of composite hydrogel sheets. *Journal of the American Chemical Society, 135*(12), 4834-4839. doi:10.1021/ja400518c
23. Schattling, P., Jochum, F. D., & Theato, P. (2014). Multi-stimuli responsive polymers – the all-in-one talents. *Polym. Chem., 5*(1), 25-36. doi:10.1039/c3py00880k
24. Liu, K., Wu, J., Paulino, G. H., & Qi, H. J. (2017). Programmable deployment of tensegrity structures by stimulus-responsive polymers. *Scientific Reports, 7*(1). doi:10.1038/s41598-017-03412-6
25. Huang, H., Petruska, A. J., Sakar, M. S., Skoura, M., Ullrich, F., Zhangm, Q., . . . Nelson, B. J. (2016). Self-folding hydrogel bilayer for enhanced drug loading, encapsulation, and transport. 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). doi:10.1109/embc.2016.7591143
26. Butvilovskaya, V. I., Popletaeva, S. B., Chechetkin, V. R., Zubtsova, Z. I., Tsybulskaya, M., Samokhina, L. O., . . . Rubina, A. Y. (2016). Multiplex determination of serological signatures in the sera of colorectal cancer patients using hydrogel biochips. *Cancer Medicine, 5*(7), 1361-1372. doi:10.1002/cam4.692
27. Hiller, J., & Lipson, H. (2009). Design and analysis of digital materials for physical 3D voxel printing. *Rapid Prototyping Journal, 15*(2), 137-149. doi:10.1108/13552540910943441
28. Behl, M., & Lendlein, A. (2007). Shape-memory polymers. *Materials Today, 10*(4), 20-28. doi:10.1016/s1369-7021(07)70047-0
29. Westbrook, K. K., Mather, P. T., Parakh, V., Dunn, M. L., Ge, Q., Lee, B. M., & Qi, H. J. (2011). Two-way reversible shape memory effects in a free-standing polymer composite. *Smart Materials and Structures, 20*(6), 065010. doi:10.1088/0964-1726/20/6/065010
30. Chung, T., Romo-Uribe, A., & Mather, P. T. (2008). Two-way reversible shape memory in a semicrystalline network. *Macromolecules, 41*(1), 184-192. doi:10.1021/ma071517z
31. Campbell, T. A., Tibbits, S., & Garrett, B. (2014). The programmable world. *Scientific American, 311*(5), 60-65. doi:10.1038/scientificamerican1114-60
32. Lendlein, A., & Langer, R. (2002). Biodegradable, elastic shape-memory polymers for potential biomedical applications. *Science, 296*(5573), 1673-1676. doi:10.1126/science.1066102
33. Ge, Q., Dunn, C. K., Qi, H. J., & Dunn, M. L. (2014). Active origami by 4D printing. *Smart Materials and Structures, 23*(9), 094007. doi:10.1088/0964-1726/23/9/094007
34. Huang, L., Jiang, R., Wu, J., Song, J., Bai, H., Li, B., . . . Xie, T. (2016). Ultrafast digital printing toward 4D shape changing materials. *Advanced Materials, 29*(7), 1605390. doi:10.1002/adma.201605390
35. Zhao, Z., Wu, J., Mu, X., Chen, H., Qi, H. J., & Fang, D. (2017). Origami by frontal photopolymerization. *Science Advances, 3*(4). doi:10.1126/sciadv.1602326
36. Khademhosseini, A., & Langer, R. (2016). A decade of progress in tissue engineering. *Nature Protocols, 11*(10), 1775-1781. doi:10.1038/nprot.2016.123
37. Holloway, J. L., Spiller, K. L., Lowman, A. M., & Palmese, G. R. (2011). Analysis of the in vitro swelling behavior of poly(vinyl alcohol) hydrogels in osmotic pressure solution for soft tissue replacement. *Acta Biomaterialia, 7*(6), 2477-2482. doi:10.1016/j.actbio.2011.02.016
38. Malachowski, K., Breger, J., Kwag, H. R., Wang, M. O., Fisher, J. P., Selaru, F. M., & Gracias, D. H. (2014). Stimuli-responsive theragrippers for chemomechanical controlled release. *Angewandte Chemie International Edition, 53*(31), 8045-8049. doi:10.1002/anie.201311047

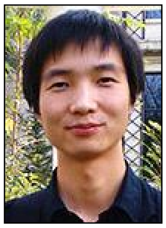
39. Hu, J., Meng, H., Li, G., & Ibekwe, S. I. (2012). A review of stimuli-responsive polymers for smart textile applications. *Smart Materials and Structures, 21*(5), 053001. doi:10.1088/0964-1726/21/5/053001
40. Huang, Y., Zhong, M., Shi, F., Liu, X., Tang, Z., Wang, Y., . . . Zhi, C. (2017). An intrinsically stretchable and compressible supercapacitor containing a polyacrylamide hydrogel electrolyte. *Angewandte Chemie International Edition, 56*(31), 9141-9145. doi:10.1002/anie.201705212
41. Irvine, S., & Venkatraman, S. (2016). Bioprinting and differentiation of stem cells. *Molecules, 21*(9), 1188. doi:10.3390/molecules21091188
42. Yakacki, C. M., Shandas, R., Safranski, D., Ortega, A. M., Sassaman, K., & Gall, K. (2008). Strong, tailored, biocompatible shape-memory polymer networks. *Advanced Functional Materials, 18*(16), 2428-2435. doi:10.1002/adfm.200701049
43. Stoppa, M., & Chiolerio, A. (2014). Wearable electronics and smart textiles: A critical review. *Sensors, 14*(7), 11957-11992. doi:10.3390/s140711957
44. Taylor, D.L., & Panhuis, M.I. (2016). Self-healing hydrogels. *Advanced Materials, 28*(41), 9060-9093. doi:10.1002/adma.201601613
45. Deng, G., Li, F., Yu, H., Liu, F., Liu, C., Sun, W., . . . Chen, Y. (2012). Dynamic hydrogels with an environmental adaptive self-healing ability and dual responsive sol–gel transitions. *ACS Macro Letters, 1*(2), 275-279. doi:10.1021/mz200195n
46. Gisby, T.A., O'Brien, B.M., & Anderson, I.A. (2013). Self sensing feedback for dielectric elastomer actuators. *Applied Physics Letters, 102*(19), 193703. doi:10.1063/1.4805352
47. Gauvreau, B., Guo, N., Schicker, K., Stoeffler, K., Boismenu, F., Ajji, A., . . . Skorobogatiy, M. (2008). Color-changing and color-tunable photonic bandgap fiber textiles. *Optics Express, 16*(20), 15677-15693. doi:10.1364/oe.16.015677

Devin Roach
Ph.D. Candidate, Georgia Institute of Technology

Devin Roach is pursuing a Ph.D. in mechanical engineering, conducting research in the Mechanics of Soft Materials and 3-D Printing Laboratory under H. Jerry Qi (B.S., Georgia Institute of Technology). His research interests include soft-active polymers, 3-D printing, and how they can be integrated to form novel structures for use in printed soft robotics and biomedical devices. He has worked on research teams at Sandia National Laboratories, Delta Air Lines, and Airbus Headquarters in Germany.

Craig M. Hamel
Ph.D. Candidate, Georgia Institute of Technology

Craig M. Hamel is pursuing a Ph.D. in mechanical engineering and is a Paper Science and Engineering Fellow at the Renewable Bioproducts Institute (M.S., New Jersey Institute of Technology; B.S., University of Mississippi). His doctoral research revolves around the cross section of additive manufacturing, renewable materials, theoretical mechanics, and continuum level simulations.



Jiangtao Wu
Ph.D. Candidate, Georgia Institute of Technology

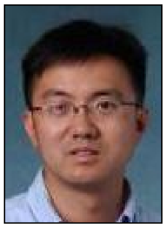
Jiangtao Wu is pursuing a Ph.D. in mechanical engineering, conducting research in the Mechanics of Soft Materials and 3-D Printing Laboratory under H. Jerry Qi (M.S., University of Chinese Academy of Sciences). Wu's research interests include 3-D printing, smart materials, active structures, and mechanics of polymers.

Xiao Kuang, Ph.D.
Postdoctoral Associate, Georgia Institute of Technology

Xiao Kuang is a postdoctoral associate in the George Woodruff School of Mechanical Engineering, (Ph.D., Institute of Chemistry Chinese Academy of Sciences; B.S., Beijing University of Chemical Technology). Kuang's research interests include of 3-D printing smart (self-healing, shape memory) materials, recyclable 3-D printing, and hybrid materials for high-performance or functional applications.

Martin L. Dunn, Ph.D.
Professor and Associate Provost for Research, Singapore University of Technology and Design

Martin L. Dunn is a professor and the associate provost for research at the Singapore University of Technology and Design (Ph.D., University of Washington). Before joining Singapore University of Technology and Design, he directed the Mechanics of Materials and Design of Engineering Material Systems programs at the U.S. National Science Foundation. Dunn has also served as associate dean for research in the College of Engineering at the University of Colorado, Boulder (CU Boulder). Also at CU Boulder, he was a professor of mechanical engineering, chair of the Department of Engineering, and held the Victor Schelke Endowed Chair. He has held positions at Sandia National Laboratories and the Boeing Company. His primary research interests include multiphysics modeling of materials, computational design, and additive manufacturing.



H. Jerry Qi, Ph.D.
Professor, Georgia Institute of Technology

H. Jerry Qi is a professor in the George W. Woodruff School of Mechanical Engineering (Sc.D., Massachusetts Institute of Technology). Before joining Georgia Tech, he was an associate professor at the University of Colorado, Boulder (2004-2013) and was a postdoctoral fellow at MIT (2003-2004). Qi is also an ASME Fellow and Woodruff School of Mechanical Engineering Fellow. His research primarily focuses on modeling, development, and 3-D printing of soft active materials. Specifically, his current research focuses on developing 3-D printing technologies for high performance polymers, 4-D printing of active materials, mechanics in 3-D printing, and active polymer design and manufacturing.

ASSAULT Ladders & the Open-Architecture Composite Structures Used to Improve Them

Austin Gurley, Ph.D.
& Ross Wesson

Introduction

In the early morning of April 7, 1776, after fighting through the night, Capt. John Barry and his crew threw ladders over the deck of the HMS Edward and took command—the first capture of a British ship by the Continental Army [1]. Long before that day, and ever since, ladders have been a staple tool of naval and land assault. They also find a place in other critical environments, including tactical military and special operations, emergency and disaster response, police and SWAT operations, climbing, and diving. Over the last several decades, military and first responder communities have continued to improve and refine ladder design and weight for deployment and small unit operations. Here we review the state of the art in assault ladder materials and design and consider where future development efforts should be directed. Studies by Deft Dynamics LLC find that ladders fabricated from composite materials provide decreased weight at a cost of increased stowed volume. There is ample room for innovation in this space, to reduce both the collapsed size and weight of a composite ladder.

Image Credit | *VIRGINIA BEACH, Va. (July 16, 2013) U.S. Navy SEALs (Sea, Air, and Land) climb a caving ladder during visit, board, search and seizure (VBSS) training on land. Photo Illustration created by HDIAC and adapted from U.S. Navy photo by Mass Communication Specialist 2nd Class (available for viewing at* http://www.

Assault ladder technologies fall into one of two categories: self-supporting (rigid) or caving/Jacob's (wire, rope, or cable). Assault ladders typically collapse into short sections for easy carry and are used for entering buildings and bridging across natural or urban rifts. Caving ladders, often fabricated from steel or Kevlar cables, can be used in descent/ascent/extraction operations. Caving ladders remain the primary platform for extraction and emergency response and currently provide little room for new/novel developments. However, advances in different materials offer the defense and first responder communities potentially game-changing improvements in self-supporting ladder technology.

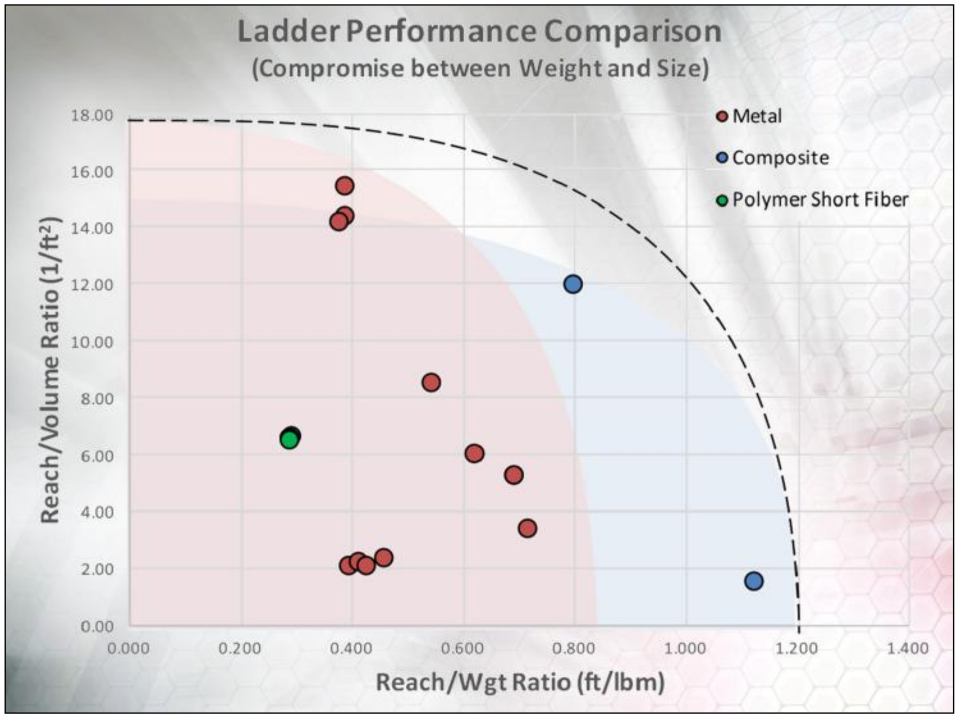


Figure 1: State-of-the-art ladders present a compromise between low weight and small collapsed size. Carbon composites push the frontier toward lower weight but are not as compact when stowed as the best metal designs.

Performance Metrics

Improvements in ladder technology primarily focus on the reach, collapsed size, and weight of ladder designs. The Department of Defense (DoD) and first responders classify and compare tactical ladders by their performance along two metrics: reach-to-weight ratio and reach-to-collapsed-size ratio. A ladder's reach-to-weight ratio is its fully extended reach divided by the weight of its segments. A high ratio in this metric is important when the ladder must be moved into place by hand or carried long distances. A ladder's reach-to-collapsed-size ratio is its fully extended reach divided by its largest segment or collapsed dimension. A high ratio in this metric is important for storage in a vehicle or vessel prior to deployment or when the ladder is transported directly by the operator as a part of his or her gear.

A Deft Dynamics performance comparison of commercially available self-supporting ladders is shown in Figure 1. The current limits of assault ladder performance are bounded by a reach-to-volume ratio of nearly 16 (here, measured in feet per cubic foot). The best designs are extraordinarily collapsible based on their ability to fold into a compact package, such as the Safariland Group Tactical Portal Ladder [2]. On the outer limit of possible reach-to-weight ratios, carbon composite ladders excel with a peak of 1.12 (feet per pound mass), such as the Atlas Devices REBS Carbon Multi Ladder [3]. However, despite their low weight, these carbon fiber ladders do not collapse into a compact package. It is a common feature of composite ladders that they typically come in larger, monolithic designs. Figure 1 reinforces the fact that achieving a high reach-to-volume ratio is driven by mechanical design—easily achieved with aluminum—whereas a high reach-to-weight ratio is achieved by the use of innovative materials. Carbon fiber composites have paved the way for many new designs that improve the weight and strength characteristics of a ladder; however, in general, the use of carbon fiber composites prevents a small collapsed size. New and more modular

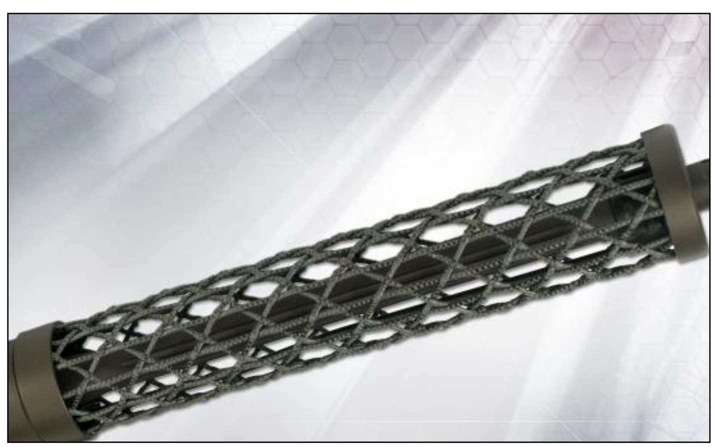


Figure 2: (left) Deft Dynamics LLC open-architecture composite ladder segment (design concept). Figure 3: (right) Deft Dynamics LLC open-architecture composite structures currently being used in the field as handguards for the M4 rifle.

Joint Expeditionary Base Little Creek-Fort Story. Navy SEALs are the maritime component of U.S. Special Forces and are trained to conduct missions from sea, air, and doncio.navy.mil/chips/ArticleDetails.aspx?ID=5921).

Specific Stiffness Comparison	O-ACS	Carbon Tube	6061-T6 AL
Axial (kNm/kg)	62.6	26	20.6
Torsion (Nm³/kg)	1363	409	183
Bending (Nm³/kg)	4489	2050	243

Table 1: Stiffness drives buckling failure, which determines the ultimate strength of trusses like O-ACS.

composite methods and materials, such as open-architecture composite structures (O-ACS), may be key to pushing past current limitations in assault ladder design (see Figure 2) [4-8].

With the goal of advancing the capabilities of composite materials and designs, Deft Dynamics has designed and implemented O-ACS structures for rugged use applications, including an M4 rifle handguard, which is currently being used in the field (see Figure 3). The breakpoints for these structures (fabricated in 15-inch segments) show great potential for use in assault ladder applications (see Table 1). Deft Dynamics has built proprietary software, Fellpoint, which accurately simulates and predicts O-ACS strength. Innovations in composites that reduce a ladder's collapsed size must focus on composite structural member interconnections, while also remembering that ultralight composites lend themselves well to large outer diameters. This can be achieved most easily by focusing on nested or telescoping structures, as has been successfully employed by some metal ladder manufacturers [9].

Summary

With an understanding of DoD and first responder requirements, two key metrics (reach-to-weight and collapsed-size-to-weight ratios) provide a clear method for comparing the raw performance of assault ladders. However, no existing ladder model achieves both weight and collapsed-volume design goals simultaneously.

Though valuable for design targets, these performance metrics do not perfectly capture all the benefits or pitfalls of a given ladder design. Certain situations may require shorter assembly time or quieter operations during ascent. The assault ladders compared here may not provide sufficient support for bridging long distances.

A successful high-value clandestine operation may demand the use of an extremely compact ladder, regardless of weight, and rescue operations often occur in abnormally high or low temperatures. Keeping these considerations in mind, the defense and first responder communities could incorporate composite materials into superior collapsible designs for next-generation assault ladders to lighten warfighter load and improve tactical and response operations. ■

References

1. History.com Staff. (2009). U.S. Navy captures first British warship. Retrieved from http://www.history.com/this-day-in-history/u-s-navy-captures-first-british-warship
2. The Safariland Group. Tactical Portal Ladder. Retrieved from http://www.safariland.com/products/body-armor/tactical-body-armor-and-gear/tactical-accessories/ladders/tactical-portal-ladder-TAC_PORT_LADDER.html
3. Atlas Devices. (n.d.). REBS Carbon Multi Ladder [Fact Sheet]. Retrieved from https://atlasdevices.com/wp-content/uploads/REBS-carbon-multi-ladder-fact-sheet.pdf
4. Gurley, A., Beale, D., Broughton, R., & Branscomb, D. (2015). The design of optimal lattice structures manufactured by maypole braiding. *Journal of Mechanical Design, 137*(10), 101401. doi:10.1115/1.4031122
5. Broughton, R., & Gurley, A. (2016, May). Connecting textile and composites; Open architecture braided composite truss structures. Paper presented at JEC Americas, Atlanta, GA.
6. Gurley, A., Branscomb, D., Broughton, R., & Beale, D. (2014, October). Rapid design of minimal-weight open-structure composite beams. Paper presented at the Composites and Advanced Materials Expo, Orlando, FL.
7. Branscomb, D., Broughton, R., Beale, D., & Gurley, A. (2014, April). Robust pre-impregnated yarn for manufacturing textile composites. Paper presented at the AATCC International Conference, Asheville, NC.
8. Branscomb, D., Gurley, A., Beale, D., & Broughton, R. (2012). Open-architecture composite tube: Design and manufacture [Abstract] (pp. 169-170). Poster presented at the Fiber Society Fall Meeting and Technical Conference, Boston, MA. Retrieved from http://www.thefibersociety.org/Portals/0/Past%20Conferences/2012_Fall_Abstracts.pdf
9. Telesteps. (n.d.). Retrieved from http://telesteps.net/

Austin Gurley, Ph.D.
Founder/CTO, Deft Dynamics LLC

Austin Gurley is the founder/CTO of Deft Dynamics LLC, where he leads a team of inventors and designers across diverse fields including ultralight composites, data and sensing systems for race cars, and shape memory robots and actuators (Ph.D., Auburn University). While pursuing his doctoral degree at Auburn University, he studied as a NASA Space Grant Consortium Fellow and designed and taught a graduate course on embedded systems in robotics. His research interests include control and design of shape memory alloy artificial muscles, textile and braided-lattice composites, and vehicle dynamics.

Ross Wesson
Founder/COO, Deft Dynamics LLC

Ross Wesson is the founder/COO of Deft Dynamics LLC, where he leads the team focused on investing in and commercializing new technologies (B.S. and B.S., University of Alabama). He is an entrepreneur with a passion for building great businesses around revolutionary technologies. Prior to founding Deft Dynamics LLC, he worked in the investment industry, most recently on Wall Street. He graduated from the University of Alabama, where he double-majored in economics and finance and minored in philosophy. He has also earned the Chartered Financial Analyst (CFA) Program credential.

Image Credit: *May 25, 2017, SYRIA - U.S. Marines with the 11th Marine Expeditionary Unit fire their M777 Howitzer during a fire mission in northern Syria as part of Combined Joint Task Force - Operation Inherent Resolve, Mar. 24, 2017. The 11th MEU was deployed in the Asia-Pacific and Middle Eastern regions and acted as a rapid response force available to conduct operations in support of U.S. Forces and allied and partner nations. More than 60 regional and international nations have joined together to enable partnered f orces to defeat ISIS and restore stability and security. CJTF-OIR is the global Coalition to defeat ISIS in Iraq and Syria. Photo Illustration created by HDIAC and adapted from U.S. Marines Photo by Lance Cpl. Zachery Laning. (available for viewing at http://www.marines.mil/Photos/igphoto/2001753020/).*

Image Credit | Pfc. Shawn Williams of the 1st Stryker Brigade Combat Team, 25th Infantry Division, based in Fort Wainwright, Alaska, gives the thumbs-up to members of his unit by a roadside bomb in the Kandahar province of Afghanistan, June 17, 2011. Photo Illustration created by HDIAC and adapted from U.S. Navy photo by Lt. j.g.

as he is evacuated after being injured
Haraz N. Ghanbari

Combat Casualty Care: Aerosol-Based Drug Delivery to the Brain

Ramesh Raliya, Ph.D.
& Pratim Biswas, Ph.D.

Background

Aerosols are fine particles suspended in a gaseous medium [1,2], and aerosol technology could be used for synthesizing novel nanomaterials with independently controlled properties, tuned specifically for a given biological application. Using engineered nanoparticles for biomedical purposes has gained popularity in the last decade due to their exceptional physicochemical properties. In the past year, aerosol technology and nanoscience combined for the rapid and non-invasive delivery of therapeutic agents into selected bodily organs [3]. This technology may benefit military personnel injured in combat.

Deployed personnel may wait hours before receiving decisive medical care due to logistical, manpower, and/or operational constraints. Therefore, warfighters injured in austere environments may benefit from advanced medical technologies that are easily carried and implemented in combat. For example, blasts from improvised explosive devices can cause concussion and sub-concussion in military personnel; these injuries are together known as mild traumatic brain injury (mTBI) [4].

mTBI has been referred to as the signature injury of conflicts in Iraq and Afghanistan, and active duty and reserve service members are at increased risk for sustaining mTBI compared to their civilian peers. Nearly 360,000 service members have been diagnosed with TBI, and 82 percent of those cases were mTBI-related [5,6]. Because of this, mTBI is an area of active investigation by the Department of Defense because blast-induced brain injury is different from more "typical" avenues for brain injury, such as motor vehicle accidents or falls due to the blast wave from combat munitions.

There are two main challenges to treating concussive injuries on the battlefield. One challenge is the logistics of medical care in an austere environment. Typical methods of administering medication rely on medical equipment that takes up significant space and often has a short shelf life. Another challenge is the difficulty of getting medication directly into the brain. The blood-brain barrier (BBB) shields the brain from receiving tissue-specific drug delivery, and drug delivery methods (such as injections or swallowed pills) are not as precise or immediately effective, thus requiring doctors to perform risky, surgically-invasive techniques [7]. A drug delivery system that effectively bypasses the BBB and decreases supplies needed could reduce mortality and morbidity due to mTBI, on or off the battlefield.

Aerosolized Non-invasive Delivery to the Brain

The novel approach of non-invasive drug delivery to the brain is based on aerosol science and engineering principles that allow for the synthesis of monodisperse nanoscale particles (which can potentially be used as a therapeutic agent or drug carrier) and delivery methods that can be used to deposit such particles in the upper regions of the nasal cavity. Aerosolized drugs administered through the nasal pathway permeate the nasal epithelium, where they can be transported to the brain through olfactory nerves [8]. The simplest and shortest path for airborne nanoparticles to reach the central nervous system is through the olfactory tract; thus, intranasal delivery could provide the fastest and potentially least invasive option to deliver therapeutic agents to target cells in the brain [3].

Recently, Washington University in St. Louis researchers investigated a proof of concept study to demonstrate that an aerosol consisting of gold nanoparticles of controlled size, shape, and surface charge can be delivered to the brains of locusts. The aerosol could reach the brain within 30 minutes after the introduction of the nanoparticle aerosol without noticeable adverse changes in the electrophysiological response.

In the past, efforts were made to deliver the substances to the brain by temporarily opening the BBB junctions using either high osmolar solutions or intracerebral injections to cross the BBB [9,10]. However, such invasive approaches may result in tissue damage and uncontrolled distribution of the drug from the point of injection [10]. To improve drug delivery to the brain while minimizing tissue damage, attempts were also made through the nasal pathway. Intranasal delivery provides fast, non-invasive delivery of medication to the brain, thereby affording the ability to treat mTBI through bypassing the BBB.

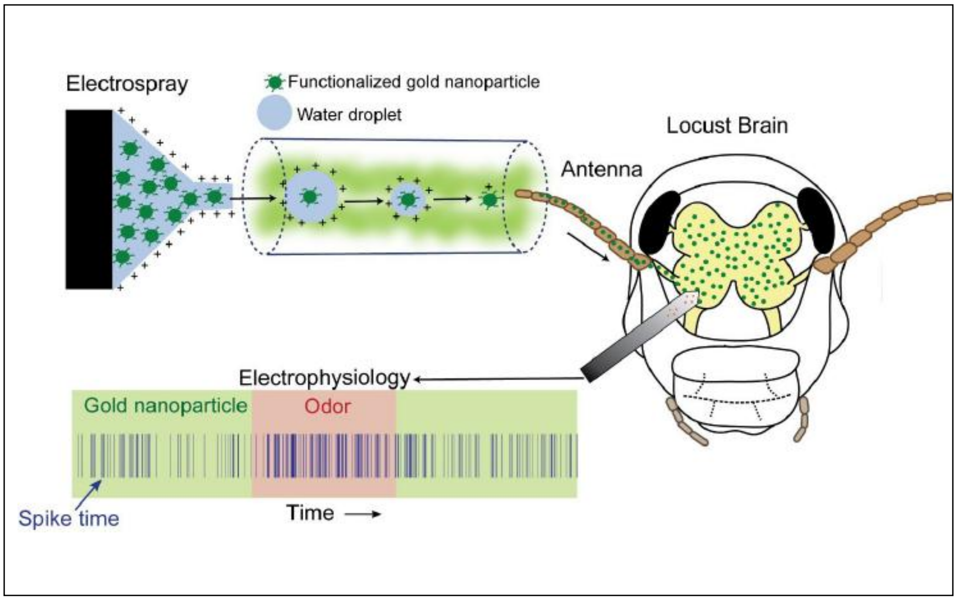


Figure 1: Schematic of an aerosol delivery of gold nanoparticles to the locust brain and monitoring the brain physiology.

Conclusion

Aerosol-based, non-invasive drug delivery has the potential to rapidly and effectively treat mTBI in service members injured in combat. Most drugs used to treat mTBI are given after diagnosis and are used to manage symptoms. However, if a medication that reduced the inflammatory cascade that occurs at the onset of a concussive injury were given immediately, the severity of the injury may be reduced and recovery time minimized. Further research must be conducted regarding particle mode of entry, the efficacy of delivery, transport mechanisms, viable pharmaceutical candidates, and long-term toxicity before the method can be further tested. ■

References

1. Friedlander, S. K. (1977). Smoke, dust and haze: fundamentals of aerosol behavior. New York: John Wiley.
2. Hinds, W. C. (1999). Aerosol technology: properties, behavior, and measurement of airborne particles. New York: Wiley.
3. Raliya, R., Saha, D., Chadha, T., Raman, B. & Biswas, P. (2017). Non-invasive aerosol delivery and transport of gold nanoparticles to the brain. *Scientific Reports, 7*, 44718. doi:10.1038/srep44718
4. Mac Donald, C., Johnson, A., Cooper, D., Nelson, E., Werner, N., Shimony, J., Snyder, A., Raichle, M., Witherow, J., Fang, R., Flaherty, S., & Brody, D. (2011). Detection of blast-related traumatic brain injury in U.S. military personnel. *New England Journal of Medicine, 364*(22), 2091-2100. doi:10.1056/NEJMoa1008069
5. Defense and Veterans Brain Injury Center. (n.d.). DoD worldwide TBI totals for 2016 Q3. Retrieved from https://dvbic.dcoe.mil/files/tbi-numbers/DoD-TBI-Worldwide-Totals_2016_Q3_Nov-10-2016_v1.0_508_2016-12-27.pdf (accessed April 19, 2017)
6. Defense Centers of Excellence for Psychological Health and Traumatic Brain Injury. (n.d.). About traumatic brain injury. Retrieved from http://www.dcoe.mil/TraumaticBrainInjury.aspx
7. Abbott, N. J., Rönnbäck, L., & Hansson, E. (2006). Astrocyte–endothelial interactions at the blood–brain barrier. Nature Reviews Neuroscience, 7(1), 41-53. doi:10.1038/nrn1824.
8. Kulkarni, K., Bhambere, T., Chaudhary, G., Talele, S., & Moghal, R. (2013). Brain targetting through intranasal route. *International Journal of PharmTech Research, 5*(4), 1441-1450. Retrieved from http://sphinxsai.com/2013/OD/PharmOD13/pdf-phamOD2013/PT=01(1441-1450)OD13.pdf
9. Neuwelt, E. A., & Dahlborg, S. A. (1987). Chemotherapy administered in conjunction with osmotic blood-brain barrier modification in patients with brain metastases. *Journal of Neuro-Oncology, 4*(3), 195-207. doi:10.1007/bf00150611Pardridge, W. (2007). Blood–brain barrier delivery. *Drug Discovery Today, 12*(1-2), 54-61. doi:10.1016/j.drudis.2006.10.01
10. Pardridge, W. (2007). Blood–brain barrier delivery. *Drug Discovery Today, 12*(1-2), pp.54-61. doi: 10.1016/j.drudis.2006.10.013

Ramesh Raliya, Ph.D.
Research Scientist, Washington University in St. Louis

Ramesh Raliya is a research scientist at Washington University in St. Louis (Ph.D., Central Arid Zone Research Institute, India). He has published more than 30 peer-reviewed publication and holds several patents. His research interests centers on exploring potential application of nanoscale properties to address global challenges in the area of nano-biotechnology, biomedical engineering, energy, and environmental applications.

Pratim Biswas, Ph.D.
Chair, Department of Energy, Environmental and Chemical Engineering, Washington University in St. Louis

Pratim Biswas is a chairman with the Department of Energy, Environmental, and Chemical Engineering at Washington University in St. Louis (Ph.D., California Institute of Technology). He has authored more than 350 peer-reviewed research articles. Biswas' research interests include aerosol science and engineering; nanoparticle technology; air quality engineering; environmentally benign energy production; combustion; materials processing for environmental technologies, environmentally benign processing, environmental nanotechnology, and the thermal sciences.

Innovation Highlight

REIMAGINING the Warfighter EXOSKELETON

Randall Alley

There are many ways to design a powered exoskeleton that assists the warfighter. Design types range from systems focused on increasing physical strength and preventing injury to the wearer (e.g., University of California, Berkeley's Human Universal Load Carrier, Raytheon's XOS 2, and Defense Advanced Research Projects Agency [DARPA]/United States Special Operations Command's Tactical Assault Light Operator's Suit [TALOS]) to reducing metabolic costs (e.g., DARPA's Warrior Web program [see Figure 1], which has led to development of the Ekso Bionics™ lower-leg exosuit and the SRI Robotics SuperFlex™ soft biofidelic actuated exosuit). Current exoskeletons remain large and cumbersome to use, require multiple actuators, and are difficult to power and control. The use of passive military exoskeletons, which do not have actuators, batteries, or electronics, is also an option (e.g., the 20 Knots Plus Ltd. MARINE MOJO™ exoskeleton and the Defense Science and Technology Group of Australia Operational Exoskeleton). Both powered and passive exoskeleton technologies may be considered biomechanical assist systems, and

Image Credit

Page 35: U.S. Army Sgt. Anthony Calvi, with the 1st Battalion, 124th Infantry Regiment completes a six-mile ruck march with a full combat load during the 2013 Region 3 Best Warrior Competition at the McCrady Training Center of Fort Jackson in Eastover, S.C., April 30, 2013. Each of the 10 states and territories in Region 3 have one Soldier and one Noncommissioned officer (NCO) competing in the four-day event, held April 29 to May 2. The first-place winners in the NCO and enlisted Soldiers categories will advance to the National Guard Bureau, national-level competition to determine which Soldier will compete in the Army's Best Warrior Competition. Photo Illustration created by HDIAC and adapted from U.S. Air National Guard photo by Tech. Sgt. Caycee Watson, U.S. Air National Guard (available for viewing at https://www.army.mil/article/112681/sgt_anthony_calvi_2013_nco_of_the_year_competitor_from_national_guard_bureau).

they are designed to improve or modify the organic human characteristics of the warfighter. The goal of most of these programs is to lighten the warfighter's burden by enhancing extant human capabilities [1]. However, little attention has been paid to the potential role an exoskeleton could play in enhancing access to mission-critical equipment while under duress. Warfighters are encumbered by bulky vests, bandoliers, and belts, which reduce mobility and make it more difficult to remain stable while in motion.

Traditionally, most of the load carried by the warfighter is concentrated in the rucksack, while the remaining load (e.g., ammo clips and body armor) is distributed within and around the tactical vest. Loads carried by the warfighter are ever-increasing in weight [2], and exoskeleton-related innovations are attempting to reduce the impact of this load—with mixed results. Acceptance of these exoskeletons has been inhibited by the weight and complexity of the systems, as well as by the discomfort experienced at areas that directly interface with the body.

Biodesigns' MOtion-capturing Fast-access Osseostabilizing™ (MOFO™) limb exoskeleton (see Figure 2) is specifically designed to redistribute mission-critical equipment to the warfighter's extremities in order to enhance ease of access. Furthermore, this technology provides a more stable platform for mounted mission-critical equipment than other exoskeleton designs, enabling the operator to sprint, crawl, jump, and crouch without restriction while retaining immediate access to a weapon, ammunition, tactical display, or other equipment. It can be worn as an individual piece on the lower leg, thigh, forearm, or upper arm—or in any combination. It is modular and adjustable and can be custom-made or purchased off-the-shelf, depending on the level of stability needed and logistical and/or mission requirements. It is designed for easy set up and breakdown.

This design mirrors a patented and patents-pending method of alternating tissue compression and release borrowed from the prosthetics industry that mitigates motion of the underlying bones of the target limb in relation to the prosthetic socket to achieve full integration between the individual and the prosthesis [3]. By taking advantage of this technology and applying it to the arm or leg of the warfighter, this limb exoskeleton provides a higher level of connection to the wearer. Because skeletal motion is accurately captured and controlled, the system becomes more integrated with the operator than a cuff or strap system.

Strap and cuff systems are inherently unstable and unwieldy when used with an object of significant mass. For this reason, operators are typically reluctant to mount equipment on the arms and legs. However, for

Figure 1: The Defense Advanced Research Projects Agency's Warrior Web program seeks to create a soft, lightweight under-suit that would help reduce injuries and fatigue and improve Soldiers' ability to efficiently perform their missions. (DOD photo)

the same reason, our own arms and legs do not impart a feeling of excessive weight or instability. A stable platform mounted on a limb that moves in unison with it, and does not allow for unwanted rotation or translation, greatly reduces perceived weight.

Another benefit of a limb exoskeleton is in the redistribution of some of the weight normally loaded into a rucksack, which have long served as the warfighter's primary load carrying equipment (LCE). Typically, all the weight carried in a rucksack is carried by the torso and hips (straps load up the trapezius muscles near the shoulders while the belt is supported by the hips). Despite the emergence of ergonomically-improved designs, there are inherent limitations to what can be safely carried, for how long, at what speed, and under what conditions. The MOFO™ can distribute some of this weight onto the limbs.By using this platform and adhering to the principles of biomechanics to maintain appropriate distances between payloads and the body's core, spinal and other injuries of the hips, knees, ankles, and feet caused by overloaded LCEs can be reduced.

Figure 2: The full arm interface of the MOFO™ exoskeleton.

Additionally, the stable limb exoskeleton can also provide a more comfortable, responsive, and proprioceptive attachment interface for full body exoskeletons still under development. A more stable interface between the operator and the exoskeleton will improve operator acceptance, mitigate injury, enhance motion capture, and reduce energy expenditure. As the intimacy of the fit is enhanced, perceived weight of the system is reduced, proprioceptive feedback is increased, and a faster response to human input is achieved.

It is increasingly important to have better, less restrictive/cumbersome solutions to enhance warfighter performance, especially when many of the conflicts involve asymmetric or irregular warfare. While the development of heavy exoskeletons is continuing at a rapid pace and systems such as TALOS approach completion, their expense and complexity will narrow their potential scope of operation and deployment. However, load carrying, load distribution, and immediate access on the battlefield for every warfighter is of paramount concern. Reimagining and redefining the role of the exoskeleton is an area in need of additional research. Exoskeletons provide a versatile, effective force-multiplying solution for special operations forces, traditional warfighters, and first responders. ■

References

1. Nair, B. (2013, April). Exoskeletons: Envisioning and expanding capabilities. *Human Performance, Training, & Biosystems Directorate Newsletter*, 3. Retrieved from http://www.acq.osd.mil/rd/hptb/docs/newsletters/2013/HPTB_Newsletter_April_2013.pdf Knapik, J. J., Reynolds, K. L., & Harman, E. (2004). Soldier load carriage: Historical, physiological, biomechanical, and medical aspects. *Military Medicine*, *169*(1), 45-56. doi:10.7205/milmed.169.1.45
2. Knapik, J. J., Reynolds, K. L., & Harman, E. (2004). Soldier load carriage: Historical, physiological, biomechanical, and medical aspects. *Military Medicine, 169*(1), 45-56. doi:10.7205/milmed.169.1.45
3. Alley, R. D., Williams, T. W., III, Albuquerque, M. J., & Altobelli, D. E. (2011). Prosthetic sockets stabilized by alternating areas of tissue compression and release. *The Journal of Rehabilitation Research and Development*, *48*(6), 679-696. doi:10.1682/jrrd.2009.12.0197

Randall Alley
CEO & Chief Prosthetist, biodesigns, Inc.

Randall Alley is the CEO and chief prosthetist of biodesigns, Inc.—a full-service clinical facility and research and development center (B.Sc., University of California, Los Angeles). He is the inventor of the patented and patents-pending High-Fidelity™ Interface (socket) System and MOtion-capturing Fast-access Osseostabilizing™ limb exoskeleton for both upper and lower limb applications. Alley was the primary interface consultant working with DEKA Research and Development Corporation on the Defense Advanced Research Projects Agency (DARPA) Luke Arm Project, and he is the PI on biodesigns' DARPA/SBIR Phase II award. Alley is the recipient of a U.S. Army Certificate of Appreciation, NovaCare Chairman's Award, and the 2016 IEEE Design Award.

Homeland Defense & Security
Information Analysis Center

Technical Inquiry Services

Four **Free Hours** of Research within our eight focus areas Available to **academia, industry,** and other **government agencies**

Focus Areas

Alternative Energy
Biometrics
CBRN Defense
Critical Infrastructure
Cultural Studies
Homeland Defense
Medical
WMD

Log on to hdiac.org to submit a technical inquiry form or contact **inquiries@hdiac.org**

Image Credit | *Air Force special tactics students swim the length of the pool with their hands and feet bound during a class before scuba training at Hurlburt Field, Fla., June 29, 2016. The class familiarizes trainees with the basics of water operations. The trainees perform tasks such as tying knots underwater, staying afloat without their arms and hands, and using snorkeling gear. Photo Illustration created by HDIAC and adapted from U.S. Air Force Photo by Senior Airman Ryan Conroy (available for viewing at https://www.defense.gov/Photos/Photo-Gallery/igphoto/2001570291/).*

Calendar of Events

December 2017

12/05/17 - 12/07/17 • Las Vegas, NV
AE Power-Gen International 2017

12/05/17 - 12/07/17 • Chantilly, VA
HDS Law Enforcement - Homeland Security Forum and Technology Exposition

12/06/17 • Brussels, Belgium
HDS Cyber Resilience Conference

12/10/17 - 12/14/17 • Arlington, VA
CIP, HDS Society for Risk Analysis 2017 Meeting

January 2018

01/17/18 - 01/18/18 • Augusta, GA
HDS Cyber Education, Research, and Training Symposium (CERTS)

01/29/18 - 01/30/18 • Destin, FL
HDS 2018 Air Force Contracting Summit

01/29/18 - 01/31/18 • Alexandria, VA
AE Operational Energy Summit

01/31/18 - 02/02/18 • San Antonio, TX
HDS Border Security EXPO

February 2018

02/06/18 - 02/08/18 • San Diego, CA
HDS WEST Conference and Exhibition

02/20/18 - 02/22/18 • Arlington, VA
CBRN Nuclear Deterrence Summit

02/13/17 - 02/14/17 • Bogota, Colombia
CBRN NCT South America 2018

HDIAC Call for Papers

HDIAC is now accepting abstracts and articles for consideration for future publications.
For more information, contact the Publications Team at publications@hdiac.org.

The HDIAC Journal is a quarterly publication, focusing on novel developments and technology in the Alternative Energy, Biometrics, CBRN Defense, Critical Infrastructure Protection, Cultural Studies, Homeland Defense and Security, Medical, and Weapons of Mass Destruction focus areas.

- Articles must be relevant to one of the eight focus areas and relate to Department of Defense applications.
- Articles should be submitted electronically as a Microsoft Word document.
- We require a maximum of 2,500 words.
- All submissions must include graphics or images (300 DPI or higher in JPG or PNG format) to accompany the article. Photo or image credit should be included in the caption.

Publications

Volume 5; Issue 2
(Publish June 2018)
Abstract deadline:
1/05/18
Article deadline:
02/02/18

Volume 5; Issue 3
(Publish April 2018)
Abstract deadline:
04/13/18
Article deadline:
05/18/18

Volume 5; Issue 4
(Publish Dec. 2018)
Abstract deadline:
07/13/18
Article deadline:
08/17/18