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TRI-SERVICE BIOTECHNOLOGY FOR A RESILIENT SUPPLY CHAIN

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ABSTRACT

Recent years have demonstrated the fragility of both military and non-military supply chains. Through biotechnology and biomanufacturing, the Department of Defense (DoD) can use readily available feedstocks to onshore manufacturing of chemicals and materials critical to defense needs and to create advanced materials with enhanced capabilities. Development of DoD's biotechnology and biomanufacturing capabilities will help secure the defense supply chain and contribute to a force that is sustainable, resilient, survivable, agile, and responsive.

To accelerate the advancement of biotechnology and biomanufactured products, the Department launched the Tri-Service Biotechnology for a Resilient Supply Chain (T-BRSC) program in Fiscal Year 2022. T-BRSC is creating a pipeline for advanced development and transition of biomanufactured materials to support defense supply chain resilience. The effort brings together Joint Service partners to leverage significant advances made over the last decade in using microorganisms to produce highly specialized bio-based chemicals that can be used to manufacture a wide variety of materials of interest to DoD.

The T-BRSC project portfolio is focused on enhanced capabilities, reduced logistics, infrastructure modernization, and cost savings. The program emphasizes the rapid prototyping of promising biotechnology research through partnerships with non-traditional commercial performers to facilitate entry of biomanufactured materials into acquisition Programs of Record and develop the Biotechnology Defense Industrial Base.

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1. INTRODUCTION

In the decades since World War II, advanced products have been developed that take advantage of globe-spanning supply chains. Some require resources grown and located internationally such as rubber, palm oil, or rare earth elements, while others require components whose manufacture has moved overseas as private industry has searched for methods of decreasing costs. In recent years the destabilizing nature of these complicated supply chains has been realized, and U.S. leadership has worked to address the issue by capitalizing on areas where the United States leads, including agricultural production and research and development. By combining these existing capabilities with the promotion of U.S. biotechnology and biomanufacturing to ensure an enduring technological and scientific advantage, the U.S. can onshore production of critical materials and chemicals, secure U.S. supply chains, and support the mission of national defense [1].

Biotechnology is a rapidly growing engineering discipline that uses living systems such as microorganisms to enable a range of technologies and capabilities. In recent decades, innovations in healthcare, pharmaceuticals, and agriculture have garnered much attention. However, biotechnology has the potential to contribute to a wider variety of defense applications including bio-based sensors, human performance and protection, manufacture of advanced materials, and production of fuels and chemicals, and has been identified by DoD as a critical technology area [2].

Biotechnology and biomanufacturing can use sustainable feedstocks that are available domestically or in operational environments to create bespoke advanced materials with enhanced capabilities; these feedstocks can also be used for the biomanufacture of known materials, chemicals, and precursor molecules through novel mechanisms. The Department already uses biotechnology to produce many products inside the DoD supply chain, but continued development of these technologies will give the warfighter enhanced capabilities and contribute to a force that is sustainable, resilient, survivable, agile, and responsive.

Over the next few decades, biotechnology and biomanufacturing are estimated to contribute up to $30 trillion dollars to the world economy [3] [4]. The United States has the potential to produce over 1 billion dry tons of nonfood biomass per year without impacting the environment or food production. This represents a significant feedstock source for domestic biomanufacturing and biotechnology that the United States can capitalize on to ensure the success of domestic biotechnology and biomanufacturing [5].

The United States has been a primary driver in the research and development of biotechnology over the past several decades, but other nations and strategic competitors are investing significant resources to dominate the field. To maintain America's technological superiority, on September 12, 2022, President Biden signed an Executive Order on "Advanced Biotechnology and Biomanufacturing Innovation for a

Sustainable, Safe, and Secure American Bioeconomy," [6] laying out a whole-of-government approach toward advancing biotechnology and biomanufacturing. In March 2023, DoD published the DoD Biomanufacturing Strategy, defining how DoD will apply bioindustrial manufacturing investments to meet this national challenge [1]. DoD's biotechnology commitment is centered on complementary investments across several programs, including the public-private partnership DoD Manufacturing Institutes Bioindustrial Manufacturing and Design Ecosystem (BioMADE) [7] and Advanced Regenerative Manufacturing Institute (ARMI BioFabUSA) [8] within the DoD Manufacturing Technology Program [9]; the Distributed Bioindustrial Manufacturing program, which will fund domestic bioindustrial manufacturing facilities to build domestic biomanufacturing capacity; and the Tri-Service Biotechnology for a Resilient Supply Chain (T-BRSC) program, which is accelerating the development and transition of biomanufactured products (see Figure 1).

2. TRI-SERVICE BIOTECHNOLOGY FOR A RESILIENT SUPPLY CHAIN

The T-BRSC program was chartered in Fiscal Year 2022 for five years and is developing a pipeline for the advanced development and transition of biomanufactured products to the tri-Services (see Figure 2). This will enhance the Department's ability to biomanufacture critical chemicals and materials, promoting defense supply chain resilience and creating vital mission support resources. T-BRSC is funding scientists and engineers from across the Services and Components, as well as their industry and academic partners, to advance and mature biotechnology and accelerate the transition of biotechnology products that use biomanufacturing, promote the ability of biomanufacturing to support the Department's goals and needs, and ensure that the Department continues to innovate and lead in the rapidly expanding areas of biotechnology and biomanufacturing.

T-BRSC's project portfolio integrates fundamental and applied research across four technology focus areas: enhanced capabilities, reduced logistics, cost-savings, and infrastructure modernization (see Table 1). Across these focus areas T-BRSC is supporting 36 projects. 9 of these are supporting the modernization of the instrumentation and facilities necessary for rapid prototyping capabilities and transition of biomanufactured products. T-BRSC is support 27 which are developing and advancing new technologies that will ensure a secure and resilient supply chain and provide the warfighter with an enduring

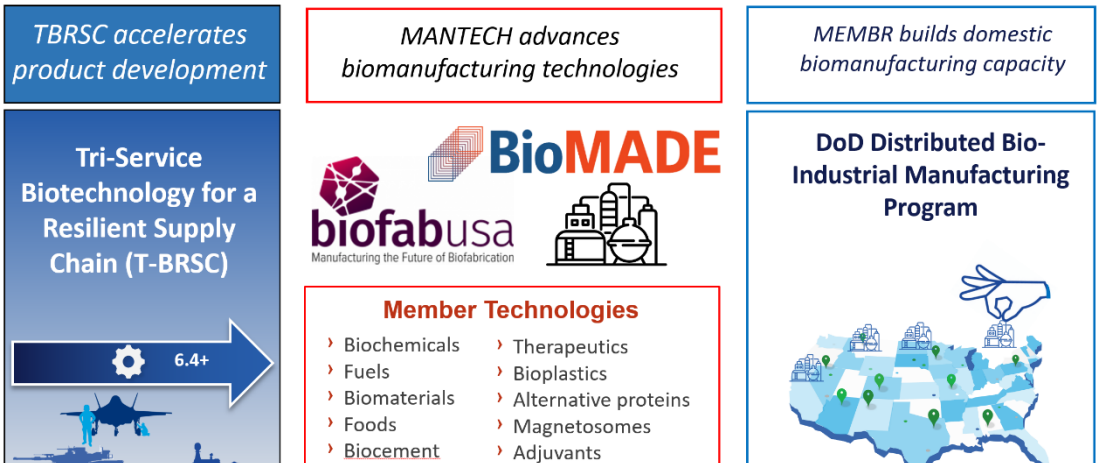

Figure 1. Complementary DoD Investments in Research & Development and Bioindustrial Manufacturing

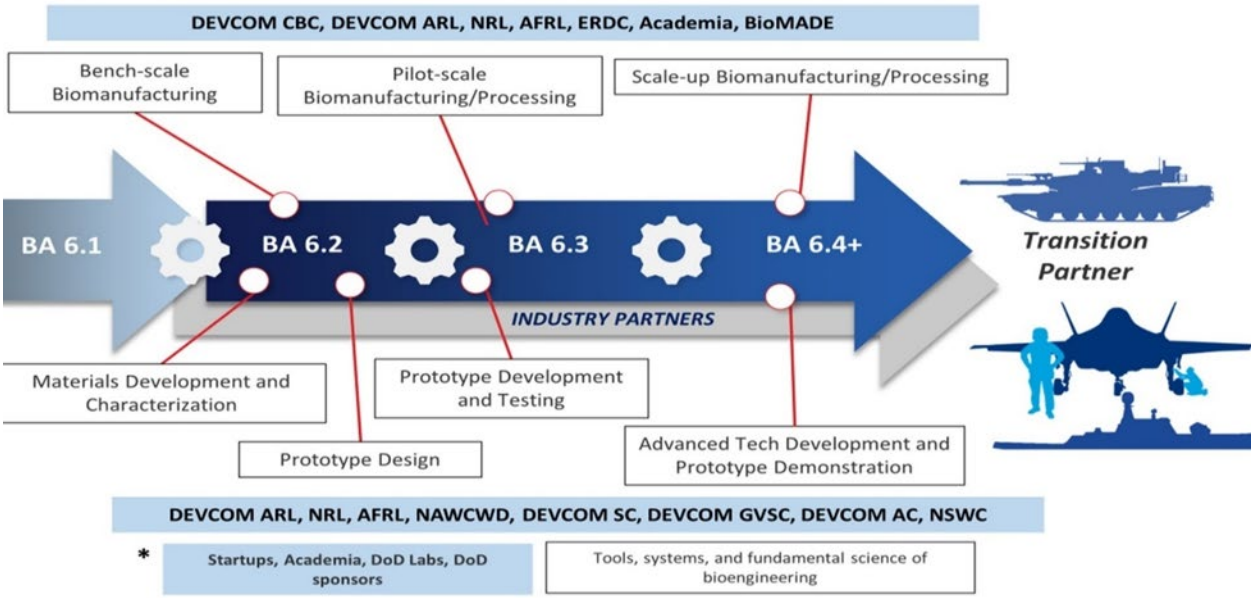

Figure 2. T-BRSC Biomanufacturing Pipeline

advantage. These projects span a wide array of DoD interests, including creation of novel materials suitable for infrastructure and warfighter textiles; production of DoD-critical chemicals, molecules, and food; use of novel feedstocks at point-of-need; and others. Representative examples of the T-BRSC project portfolio are described below.

2.1. Enhanced Capabilities

The enhanced capabilities focus area includes the biomanufacturing of advanced materials that provide an enduring advantage, including materials for aerial platforms and thermal protection, personal protection equipment, and equipment protection. Researchers in the enhanced capabilities focus area use the tools of biotechnology to identify molecules with naturally present characteristics of interest, improve these characteristics, biomanufacture them at a high level of purity, and determine how to use them to create novel materials. Examples of T-BRSC-funded projects in this focus area include:

Biomimetic Spider Silk for IR Signature Management & Composite Reinforcement

Principal Investigator: Joseph Estevez, Naval Air Warfare Center Weapons Division China Lake

Spider silk is one of the strongest known natural fibers and is lighter than carbon, five times stronger than steel, and three times tougher than Kevlar. While it is difficult to harvest natural spider silk, recombinant silks that mimic the amino acid sequence can be biomanufactured at pilot scale by Technology Holdings LLC (THL). In collaboration with THL and the U.S. Army Combat Capabilities Development Command (DEVCOM) Soldier Center, Naval Air Warfare Center Weapons Division China Lake (NAWCWD) previously demonstrated a method to fabricate mats of spider silk using new, high-molecular weight spider silk proteins. This allows the creation of silk mats with complex geometries that confer characteristics ideal for use in infrared signature management textiles.

In this effort, researchers are producing spider silk with unique geometries and identifying the optimum parameters for manufacture of spider silk material systems with ideal mechanical and signature management performance. Upon completion, biomimetic spider silk will be used for materials with tailorable mechanical and signature management properties for use within textile and composite material systems, leading to new innovative capabilities and performance. The inherent characteristics of electrospun spider silk have demonstrated advantageous infrared (IR) signature properties, and biomimetic variants are already being produced that have the potential to further improve the IR signature properties of spider silk.

Table 1. T-BRSC Project Portfolio

Focus Area	Description	#
Enhanced Capabilities	Biomanufacturing advanced materials that provide an enduring advantage, including materials for aerial platforms and thermal protection, personal protection equipment, and equipment protection. Enhanced capabilities can include signature management, increased thermal capacity, improved strength to weight ratios among many others.	8
Reduced Logistics	Biomanufacturing molecules that reduce the logistical burden for operating in contested environments, such as high-performance, high-energy density fuels. Point-of-need biomanufacturing of critical molecules in adverse or operational environments.	15
Cost-Savings	Biomanufacture of expensive chemicals or molecules, drop-in replacements for chemicals that are being phased out of use, and recovering valuable elements from recycled military assets, such as the extraction of rare earth elements from waste streams using biomolecules.	4
Infrastructure Modernization	Much of the biotechnology and biomanufacturing infrastructure housed at DoD laboratories is several decades old. T-BRSC is supporting the modernization of the instrumentation and facilities necessary for rapid prototyping capabilities and transition, including the creation of a secure tri-Service digital backbone to facilitate data integration, standardization, and access to DoD high-performance computing resources. Infrastructure modernization will enable biomanufacturing to address emerging DoD requirements rapidly and flexibly.	9

<u>High-Temperature Biomanufactured Composite Materials</u>

Principal Investigator: Ben Harvey, Naval Air Warfare Center Weapons Division China Lake

The High-Temperature Biomanufactured Composite Materials effort is a collaboration between NAWCWD and BioMADE industry members Cambium-USA and Amyris that is developing novel materials for thermal protection. Using a combination of biomanufacturing, chemistry, and material fabrication, the project is creating advanced composite materials with exceptional thermal stability and enhanced fire-resistance. Applications for these new composite materials include next-generation mortar tubes, fire-resistant housings for lithium-ion batteries, high-temperature missile cases, fire-resistant coatings for airframes, and carbon-carbon composites for use in hypersonic systems or reentry vehicles.

New bio-based mortar tubes (developed in collaboration with the DEVCOM Armaments Center at Watervliet Arsenal) will weigh less compared to conventional metal tubes while simultaneously enabling higher rates-of-fire, and increased firing duration time for Army infantry units. Fire-resistant “battery boxes” will enhance platform survivability and warfighter safety. High-temperature missile cases will enable the development of weapon systems with increased range and improved mission flexibility. Finally, biosynthetic fire-resistant coatings will enhance the survivability of aircraft, ships, and ground vehicles.

2.2. Reduced Logistics

The reduced logistics focus area is developing biomanufacturing technologies

that reduce the logistical burden for operating in contested environments. This can include infrastructure needs such as building materials and technologies that address logistical burdens, as well as those helping to secure supply chains through domestic biomanufacture of critical molecules or operational point-of-need manufacturing capabilities supporting the forward-deployed warfighter. The diversity of available feedstocks for biomanufacturing provides new solutions for capability gaps experienced during operations that are not hampered by vulnerable supply chains. Examples of T-BRSC-funded projects in this focus area include:

Ultra-Pure High Surface Area Bio-Engineered Charcoal for Large Caliber Ignition Systems

Principal Investigator: Eugene Rozumov, DEVCOM Armaments Center

Charcoal is a frequently used resource by DoD with numerous applications. Military charcoal is produced through destructive distillation of a variety of wood types, resulting in a high degree of batch-to-batch variability. Depending on the application of the charcoal, this variability can result in undesirable characteristics in the end-product. To address this issue, the U.S. Army Combat Capabilities Development Command Armaments Center (DEVCOM AC) is examining a charcoal biomanufactured from viruses by DEVCOM Chemical Biological Center (DEVCOM CBC). This highly controlled process results in the consistent production of charcoal with a variety of desirable characteristics, including a high surface area available for combustion due to its porosity as well as a high level of purity.

In this effort, DEVCOM AC is testing the ability to use this biomanufactured charcoal as a drop-in replacement in comparison to standard charcoal for applications of interest to boost performance. After successful testing, the viral charcoal will have a technology readiness level (TRL) of 4, and further work and testing will be conducted to prepare the biomanufactured charcoal for transition to programs of record that need pure charcoal. This work will produce a drop-in-replacement for a DoD-critical resource with improved characteristics, resulting in enhanced capabilities and a novel supply chain.

Demonstration of Phage-Enhanced Biological and Electrochemical Processes to Produce Green Ammonia Fuel from Blackwater

Principal Investigator: Benjamin Thomas, Ground Vehicle System Center

Contingency bases generate a highly concentrated wastewater from latrine and kitchen systems called blackwater. This blackwater contains high concentrations of nitrogen, carbon, ammonia, and other resources, which if reclaimed would be a valuable resource in addition to the treated blackwater itself. Current strategies for wastewater management are varied according to base size, general operational standards, contractor services, and location, and include burn-out latrines, chemical latrines, contractor collection and removal, sewage lagoons, and leach fields, for example. These methods are neither technically sound nor environmentally friendly, and the current state-of-the art alternatives for blackwater treatment are energy-intensive and unable to fully reclaim available resources.

Researchers at DEVCOM Ground Vehicle Systems Center (GVSC) and Army Research Lab (ARL) funded by T-BRSC have designed a procedure for point-of-need

biofuel generation and wastewater treatment using phage virus to enhance blackwater treatment and increase ammonia accumulation and water reclamation. By integrating this biological method with existing electrochemical technologies, the new treatment procedure is an energy-positive strategy that produces treated water as well as biofuels such as methane and ammonia. When fully operational, the ammonia will be extracted and used in a fuel cell for on-site energy uses, resulting in a net energy positive system. This will significantly improve the sustainability of base operations and use waste to manufacture valuable biofuel resources.

Biocementation for Agile Combat Employment

Principal Investigators: Mitchell Meade and Maneesh Gupta, Air Force Research Laboratory Materials and Manufacturing Directorate

Ensuring Joint Force moment into and within a theater is crucially important to operational success. Infrastructure is often not available, and when present may be severely limited. Collaborative work between Air Force Research Labs, Air Force Civil Engineering Center, Engineer Research and Development Center (ERDC), and industry partners has developed a biocementation technology that uses a naturally occurring bacteria along with feedstock chemicals of urea and calcium chloride that can be sprayed directly on the ground for surface hardening and stabilization. This bacterium catalyzes the formation of calcium carbonate, which increases the soil strength by binding soil particles. Biocementation occurs within 72 hours and increases soil hardness by an order of magnitude at operationally relevant depths.

The T-BRSC-funded Biocementation for Agile Combat Employment (BACE) initiative is building on previous work to operationalize biocementation technology. BACE is working to develop and scale up shelf-stable, ready-to-spray biocementation bacteria, reducing the need for on-site fermentation infrastructure and decreasing overall time of the process. Ready-to-spray biocement will be deployable by DoD warfighters without biotechnology expertise. They will use commercially available equipment that can be transported or sourced in-theater in order to rapidly construct expeditionary infrastructure such as runway and ramp augmentation, road and landing zone hardening, soil stabilization and dust abatement, infrastructure repair, and non-traditional launch and landing zones. Completion of the BACE project will result in the maturation of biocementation technologies to TRL 7 and be followed by operationally relevant technology demonstrations and transition. Completion of BACE will result in enhanced infrastructure capabilities, decreasing the logistical burden and supply chains necessary in contested environments and providing Just in Time/Just Enough rapid infrastructure construction.

Synbio Food Production at the Point-of-Need for Nutritionally Tailored Rations

Principal Investigator: Nicole Farhadi, DEVCOM Soldier Center Combat Feeding Division

Contested logistics pose critical threats to warfighter supply chains, including the ability to provide adequate nutrition to the warfighter. This can be addressed through point-of-need biomanufacture of nutritional products. Researchers at Defense Advanced Research Projects Agency, Office of Naval Research – Global, and BioMADE have demonstrated the fermentation of safe nutritional products. This effort is focused on

advancing these technologies with the end goal of warfighter nutrition on demand, using feedstocks and materials already present in the operational environment. Led by DEVCOM Soldier Center Combat Feeding Division, this T-BRSC-funded effort is accelerating the advancement of select biomanufactured nutritional products and developing a full-scale, semi-autonomous point-of-need food biomanufacturing system with an expected TRL/manufacturing readiness level (MRL) 6 for demonstration and transition. Completion of this research will result in significant improvements to the Department's ability to provide nutrition to the warfighter in austere and contested environments.

2.3. Cost Savings

The cost savings focus area is devoted to biomanufacture of traditionally expensive chemicals or molecules, drop-in replacements for chemicals that are being phased out of use, and recovering valuable elements from recycled military assets, such as the extraction of rare earth elements from waste streams using biomolecules. These projects demonstrate the contributions that biomanufacturing can make to DoD's supply chain both when critical molecules are rare or sourced outside of the United States and in response to domestic policy changes and the need to shift production of critical chemicals away from hazardous or petrochemical based processes. Examples of T-BRSC-funded projects in this focus area include:

Biotechnology Enhanced and Enabled REEcovery
Principal Investigator: Ed Perkins, U.S. Army Engineer Research and Development Center

Rare earth elements (REE) are essential for many advanced technologies such as hard drives and laser components. China currently controls over 60 percent of global REE production and over 90 percent of world REE processing and has begun to restrict export of certain critical metals and REE. U.S. mining, production, and processing of REE has been limited as current approaches for recovering and purifying individual REE are not environmentally friendly, are energy and solvent intensive, and cannot easily separate individual REE.

To address these drawbacks and strengthen the domestic REE supply chain, the T-BRSC Biotechnology Enhanced and Enabled REEcovery (BEER) project – composed of tri-Service researchers from the U.S. Army Engineer Research and Development Center (ERDC), DEVCOM ARL, Air Force of Scientific Research, and DEVCOM Chemical Biological Center – is developing reliable biology-based approaches that can economically separate and recover individual REE from a diverse range of domestic sources including ore, mine tailings, e-waste, acid mine drainage, and contaminated groundwater. The project takes advantage of microbes in the environment that have evolved to isolate, bind and sequester REE from rocks and other sources using organic acids and REE-binding proteins in order to live under extreme conditions. Due to the constrained nature of the REE supply chain, it is of critical importance that DoD identify alternative sources of REEs. Successful completion of this effort will enable the domestic reclamation of REEs, securing the supply chain of REEs necessary for the manufacture of advanced defense technologies.

Biomanufactured Non-Hazardous Solvent for Paint Removal & Cleaning
Principal Investigator: Nicholas Wilson, Air Force Research Laboratory, Materials and Manufacturing Directorate

In 2019, the Environmental Protection Agency banned the export and commercial sale of methylene chloride, a hazardous chemical commonly used by DoD as a paint stripper and chemical coating removal agent. While non-hazardous alternatives have been suggested, multiple solvents must be used to achieve the same functionality as methylene chloride, and significant additional work is involved. There are currently no non-hazardous alternatives with comparable performance for DoD applications. BioMADE industry member Visolis has developed a non-hazardous solvent that is biomanufactured from cellulosic biomass, a widely available feedstock.

In this T-BRSC-funded effort, AFRL researchers will evaluate the biomanufactured solvent for paint removal, cleaning, and degreasing applications to determine if it meets the performance characteristics necessary to be qualified to military specifications. If successful, the biomanufactured solvent will undergo pilot scale-up and full-scale demonstration. Replacement of methylene chloride with this non-hazardous biomanufactured solvent will allow maintenance depots to reduce their chemical inventory and training needs, simplifying supply chains and logistics and decreasing the associated costs.

3. CONCLUSION

The T-BRSC program is supporting a wide spectrum of projects with diverse requirements and transition pathways. To support T-BRSC project transitions, the T-BRSC program management office is developing customized transition plans for each project. The office will work closely with the investigators to identify transition pathways and ensure that operators, technology integrators, program executive officers and others at Ground Vehicle System Center and across the Department are aware of the advantages and capabilities that biotechnology and biomanufacturing can bring to the warfighter and to the Department as a whole.

Past decades have seen how advances in manufacturing technology revolutionized the Department's capabilities, and biomanufacturing will join technologies like additive manufacturing in redefining what is possible for the defense industrial base. Through the projects funded by T-BRSC and the tri-Service scientists and engineers conducting them, T-BRSC will provide the warfighter with novel and advanced biotechnology products, create a vital mission resource, and support the domestic defense bioindustrial base, helping ensure the future global bioeconomy is made in America.

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