White Paper for Powering the Army of the Future

Title: Multi-fuel Capable Hybrid-Electric Propulsion

(Applicable to both Tier 1 and Tier 2)

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Multi-fuel Capable Hybrid-Electric Propulsion

The Army's Multi Domain Operations (MDO) is to effectively support the Joint Force in the rapid and continuous integration of all domains of warfare. This requires extensive communications and information processing, particularly with the large number of unmanned systems which are teamed with manned systems. Unmanned air and ground systems will play critical roles in executing new capabilities for MDO. They will have large impacts on the close fight and deep maneuver areas. However, these advanced capabilities will require more energy and power. Furthermore, these unmanned systems need to perform longer missions than today. The current energy and power solutions for unmanned systems are extremely limited because technologies have not been developed in the power range from 0.5 kW to 200 kW. All of the current Army unmanned system power are provided by engines developed for ground transportation such as motorcycles, race cars, or diesel passenger cars. These engines are developed to operate on commercial fuels that are produced according to specific fuel property regulations. However, the Army's unmanned systems use jet fuels whose key properties such as ignition quality and viscosity are unregulated, thus key properties can vary over a wide range from gasoline (alcohol for bio-derived jet fuel) to diesel fuels. Unlike commercial mobile power, the military mobile power should be operated at extreme conditions in terms of temperatures and altitudes. Thus, the component technologies developed for ground vehicles have major limitations for altitudes above 10,000 ft. Furthermore, unmanned aircraft engines are significantly nosier than the ground vehicles, in part because their combustion is much more rapid at altitude, which is further worsened when combined with low ignition quality fuels. This poses acoustic signature concerns.

The demand for more power has been continuously increasing as new advanced capabilities are added to mobile systems. However, as the choice of the engines is limited and reliable new engines are unavailable, the engines are pushed outside of their design limits to produce more power. This often leads to component or system failure. Even for the new unmanned system developers, one of their challenges is the lack of power systems that can meet Army requirements. Until now, the Army has not invested much in power system development for unmanned systems. The common solution has been to rely on industry; however, industry has not been developing technologies to solve problems unique to the Army and has not invested in new market areas due to unclear business cases.

For at least next 10-15 years, jet fuels will still be the major energy source for the U.S. Army to power ground, air and soldier tactical power systems. Although the battery technology has significantly advanced, it is unlikely to meet the energy requirements for the entire range of Army mobile systems in the next 15 years. In addition, *Dr. Michael Griffin, Under Secretary of Defense for Research and Engineering, announced at the McAleese 11th Annual Defense Program Conference on 4 March 2020 that "the U.S. DoD is starting a new initiative, a new manufacturing innovation center to create its own fuel using synthetic biology methods."* Thus, it is likely that the U.S. DoD will produce and use more bio jet fuels in the future. However, this poses a great challenge to the Army mobile and stationary power and energy as the Army mostly uses intermittent combustion engines (due to power constraint) that are sensitive to fuel properties.

In FY20, the CCDC Army Research Laboratory (ARL) started the Army's first power and propulsion program to address fundamental challenges in materials, design, and sensing and control methods. This effort will help the industry accelerate the development of new component technologies and power systems for future unmanned systems in the power range of 5-200 kW (typical power range for unmanned aircraft systems). These technologies are also applicable to component technologies for Army's Next Generation Combat Vehicles, Future Vertical Lift, and Soldier tactical power.

The new program, *Multi-fuel Capable Hybrid-Electric Propulsion (MCHEP)*, is focused on the advancement of technologies for Army mobile power applications including unmanned aircraft systems, unmanned ground systems, and air launched effects. Design of hybrid-electric propulsion requires optimization at the system level. ARL has performed multiple studies to evaluate different hybrid-electric power configurations, in collaboration with academia, industry and other Army organizations using existing system modeling tools. Through this process we have learned that currently available tools demonstrate large deviations in system performance benefit predictions. Furthermore, most of the tools have never been validated with experimental data. One of the reasons is the lack of data for validation. To overcome these issues, an advanced modular hybrid-electric optimization and integration tool (HEART) is being developed as part of the MCHEP program to guide the development of hybrid-electric propulsion through the prediction of system performance benefits. ARL has several DoD unique experimental capabilities designed for unmanned system power and propulsion to generate the experimental data needed to verify and validate the tool being developed.

Figure 1 shows the MCHEP phase 1 technology transition plan. The strategy used will *shorten the technology development timeline enabling delivery of components or systems in 10-15 years by closely collaborating with industry from the beginning of the program* (historically this process has taken 25-30 years). Specific technologies include ignition assistant, advanced aluminum alloys, advanced materials for fuel systems, advanced electrified turbocharging, and hybrid-electric optimization and integration technologies. *The technologies coming out of the MCHEP program are perfectly aligned with the future direction of the U.S. DoD energy solution: synthetic bio-derived fuels.* The core engine for the current demonstration will be an inverted rotary-type engine for compactness and weight reduction, although these technologies are applicable to any current or future intermittent combustion engines.

A primary challenge for Army mobile power systems is that jet fuels (and future bio fuels) with unregulated fuel properties lead to ignition difficulties at extreme conditions, resulting in underperforming mobile power. A specially designed ignition assistant is being developed to control ignition of jet fuels in intermittent combustion engines for unmanned systems. The effort is focused on the ignition assistant probe design and materials to optimize ignition probability across all engine operating conditions. Another challenge with utilizing jet fuels is a result of their low viscosity and lubricity which cause scuffing and wear in high-pressure fuel systems. This also leads to underperforming mobile power and component failures. New materials and designs are being developed for high-pressure fuel systems to extend the fuel system component life and performance. For unmanned systems, the ratio of an engine to the platform weight is quite high, meaning that the engine weight significantly influences the payload of the platform. Thus, lightweight aluminum alloys have been developed to reduce the engine weight, while ensuring it is robust under extreme thermomechanical stresses. ARL is also developing an electrified turbocharger which can produce up to 20% more power without additional strain on the core engine. The use of this technology for unmanned aircraft systems is ideal as the unmanned aircraft engines mostly operate at maximum power for takeoff and between 40-70% of maximum power for cruise or loiter. Furthermore, the differential pressure across the turbine wheel is extremely high at altitudes due to the low ambient pressure. All these allow quite high exhaust enthalpy that will be recuperated by a small compact generator located just downstream of the turbine wheel. Use of a compact generator will also help reduce the turbocharger speed as it will extract some of the exhaust energy. High turbocharger speed due to high differential pressure has always been a challenge for unmanned aircraft applications.

Table 1 shows the performance characteristics of a 2-kW multi-fuel capable hybrid-electric propulsion which is currently at TRL 5+ (applicable for Tier 1). Tables 2 and 3 show the performance characteristics of 19-kW multi-fuel capable hybrid-electric propulsion with an electrified turbocharger for a tactical power and a UAS application, respectively (applicable for Tier 2).

Future Army's advanced capabilities will require more energy and power to effectively support the MDO for the Joint Force. The current industry solutions cannot provide the required power for future unmanned systems for reliability and extended operation. Furthermore, the current component technologies will increase operation and maintenance cost as they are not designed for military applications in which the fuel properties and ambient conditions are extreme compared to the commercial sector. The MCHEP technologies provided in this white paper address the fundamental challenges in materials, design, and sensing and control methods, to accelerate component technology development to power the Army of the Future. The ARL's investment in the fundamental challenges will leverage the efforts of industry to deliver mobile power technologies that meet Army requirements.

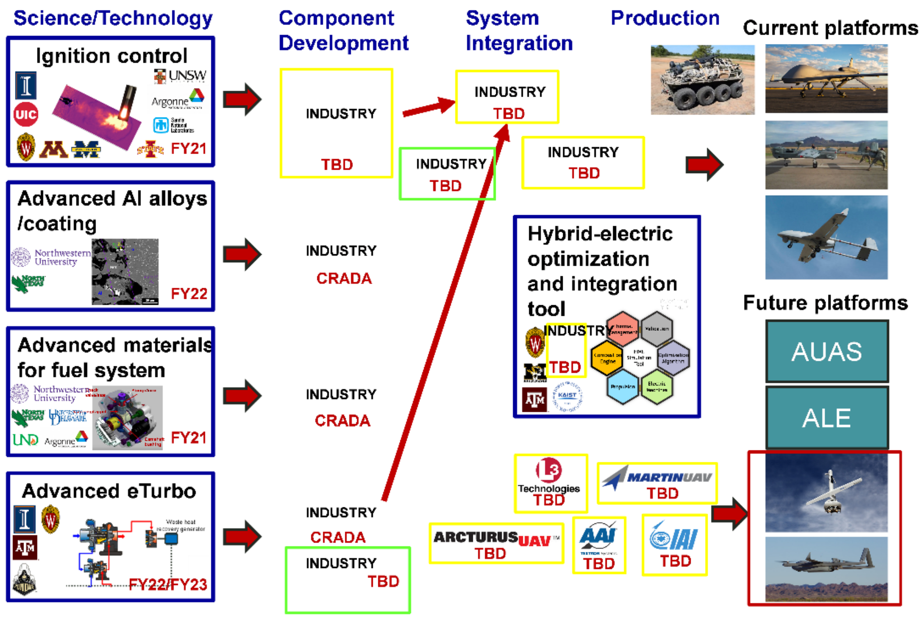

Figure 1. MCHEP phase I technology transition plan (the industry partners are hidden)

Table 1. Performance characteristics for a 2-kW power (Tier 1)

Parameters	Values	Unit	Comments
Specific energy (fuel)	42	[MJ/kg]	jet fuel energy density
Energy sources	multi fuels	[]	conventional and bio jetfuels/diesel
Specific energy for a generator for a 72-hr mission	2059	[Wh/kg]	fuel mass=0.208 kg/kW-h*19kW*72 (mission hr)*1/3 (run time)=95 kg energy available through a generator and fuel=273 kWh
Power output (engine)	3.7	[kW]	engine power
Electric output	2	[kWe]	
Power density	>1	[hp/kg]	use of light Al alloy
Engine efficiency	>35	[%]	based on engine cycle analysis using GT Power
Hybridized generator set weight	19.0	[kg]	3.5x reduction in weight over MEP95-501A comparable 2 kW heavy-fueled generator
Volume (generator set)	4x lower	[L]	4x reduction in size over MEP95-501A comparable 2 kW heavy-fueled generator
Durability/engine life	1500	[hrs]	4500+ hrs as hybrid with reduced duty cycle
Vulnerability to attack and disruption	Mid	[]	lower than the current systems due to lower acoustic and thermal signatures
Portability/mobility	High	[]	compact size-core engine 5-10x smaller
Supply/maintenance concerns	Low	[]	standard jet fuels/locally available fuels. Less number of components for maintenance
Unit cost	TBD	[$K]	depends on the requirements but will be lower than the current genset
Safety issues	Low	[]	use of less volatile fuels
Personnel training requirements	Low	[]	standard engine/component training
Policy/regulatory concerns	None	[]	proven technologies
Engine displacement	0.07	[L]	3 combustion chambers - compact size compared to reciprocating engine
Engine brake specific fuel consumption	<240	[g/kW-h]	
Core engine scalability	1-500	[kW]	
Core engine	Inverted rotary	[]	
Service ceiling for UAS	10000	[ft]	

Table 2. Performance characteristics for a 19-kW tactical power (Tier 2)

Parameters	Values	Unit	Comments
Specific energy (fuel)	42	[MJ/kg]	jet fuel energy density
Energy sources	multi fuels	[]	conventional and bio jetfuels/diesel
Specific energy for a generator for a 72-hr mission	2059	[Wh/kg]	fuel mass=0.208 kg/kW-h*19kW*72 (mission hr)*1/3 (run time)=95 kg energy available through a generator and fuel=273 kWh
Power output (engine)	19	[kW]	target engine power
Electric output	12	[kWe]	assume 75% efficiency for generator set
Power density	>1	[hp/kg]	use of lightweight materials
Engine efficiency	>40	[%]	based on engine cycle analysis using GT Power
Hybridized engine weight	15.6	[kg]	generator weight=37.6 kg (estimated). >10x lighter than a comparable 10kWe TQG MEP 803a generator
Volume (engine)	19.2	[L]	
Volume (generator set)	30	[L]	
Durability/engine life	1500	[hrs]	4500+ hrs as hybrid with reduced duty cycle
Vulnerability to attack and disruption	Mid	[]	lower than the current systems due to lower acoustic and thermal signatures
Portability/mobility	High	[]	compact size-core engine 5-10x smaller
Supply/maintenance concerns	Low	[]	standard jet fuels/locally available fuels. Less number of components for maintenance
Unit cost (target)	<20	[$K]	
Safety issues	Low	[]	use of less volatile fuels
Personnel training requirements	Low	[]	standard engine/component training
Policy/regulatory concerns	None	[]	proven technologies
Engine displacement	0.208	[L]	3 combustion chambers - compact size compared to reciprocating engine
Engine brake specific fuel consumption	<208	[g/kW-h]	
Core engine scalability	1-500	[kW]	
Core engine	Inverted rotary	[]	
Service ceiling for UAS	10000	[ft]	

Table 3. Performance characteristics for a 19-kW unmanned system power (Tier 2)

Parameters	Values	Unit	Comments
Specific energy (fuel)	42	[MJ/kg]	jet fuel energy density
Energy sources	multi fuels	[]	conventional and bio jetfuels/diesel/gasoline
Power output (engine)	19	[kW]	target engine power
Power density	1.4	[hp/kg]	use of light Al alloy
Engine efficiency	>40	[%]	based on engine cycle analysis using GT Power
Hybridized engine weight	16.4	[kg]	15% weight increase for mild hybridization (electrified turbocharger)
Volume (engine)	19.2	[L]	
Endurance	28.8	[hrs]	15% additional power from eTurbo, endurance time can increase the platform size is increased. The current Gray Eagle Extended Range endurance time is 42 hrs which is powered by one 180-hp diesel engine.
Durability/engine life	>2500	[hrs]	performance in austere or hazardous environments or under shock or damage
Vulnerability to attack and disruption	Mid	[]	lower than the current systems due to lower acoustic and thermal signatures
Portability/mobility	High	[]	compact size-core engine 5-10x smaller
Supply/maintenance concerns	Low	[]	standard jet fuels/locally available fuels. Less number of components for maintenance
Unit cost	<40	[$K]	use of advanced materials and components for more reliability
Safety issues	Low	[]	use of less volatile fuels
Personnel training requirements	Low	[]	standard engine/component training
Policy/regulatory concerns	None	[]	proven technologies
Engine displacement	0.208	[L]	3 combustion chambers - compact size compared to reciprocating engine
Engine brake specific fuel consumption	<208	[g/kW-h]	
Core engine scalability	1-500	[kW]	
Core engine	Inverted rotary	[]	
Service ceiling	20000	[ft]	Group 3 Future Tactical UAS (FTUAS)
UAS speed	0-90+	[kts]	Group 3 Future Tactical UAS (FTUAS)