**Fuel Flexible Engine-Generators with High Power & Energy Densities for Future Unmanned Aircraft Systems and Soldiers**

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**1. Executive Summary**: There are limitations to the range of small Unmanned Aircraft Systems (UAS) along with critical power generation gaps for Soldiers stemming from the respectively low energy density of lithium (Li) ion batteries. The use of combustion using conventional fuels (liquid and gaseous based) can provide a significant range benefit for both UAS and Soldiers given their magnitude increase in mass and volume specific energy over Li-ion batteries (Figure 1). Current combustion engines on the appropriate power generation scale needed (mesoscale: less than 2 L total volume) are beset by low efficiencies. However, employing the evolving technology of Additive Manufacturing (AM) changes the paradigm of construction for internal combustion engines (ICEs) that opens new avenues of efficiency while reducing size and weight. Current Tier 2 efforts at the TRL 4 level by our group include the successful testing (Figure 2) of an AM-enabled ICE constructed in cooperation with the Army Research Laboratory (ARL) (Gray 2020). Looking towards 2035, utilizing advances in AM to move from this existing ICE to a novel free piston engine (FPE)-linear generator (LG) design promises high efficiencies, complete fuel flexibility, and direct generation of electricity for hybrid configurations at a minimum of weight with reduced noise and exhaust signatures. This facilitates the single fuel forward concept while allowing for localized fuel compatibility and the continued advancement of alternative fuels. Overall, this enables Army multi-domain operations (MDO) by delivering a modernized power & energy (P&E) solution that draws upon an emerging technology.

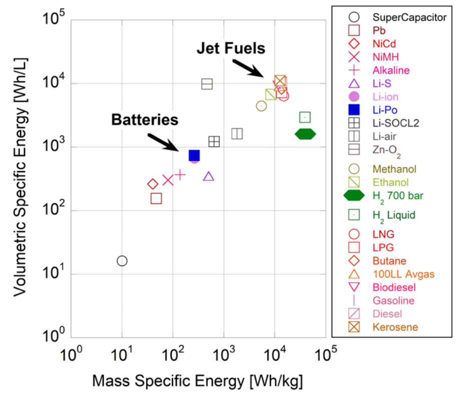

Figure 1. Different energy sources for UAS and Soldiers

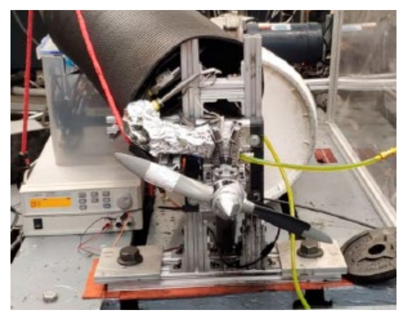
Figure 2. AM engine propeller test setup at the University of Kansas

**2. Current P&E Technology and Research**: The large majority of UAS employed by the United States (US) military are a single platform with a power plant equal to 250 W (Military.com 2014). Research in the UAS power plant field finds that Li-ion battery range is limited on the 200-1000 W level (Stolaroff et al. 2018) and with UAS usage expected to grow from 25% to 70% of the Department of Defense fleet by 2035 (U.S. Department of Transportation 2013), this is problematic. With respect to US Army Soldier power requirements, their energy demands are around 500 W (Patil et al. 2004) with a critical power generation gap noted between the 100 and 1000 W levels (Aten et al. 2015). Here, the average Army troop carries up to 23 batteries weighing 14 pounds on a three-day patrol and the need to resupply these batteries can reduce their combat radius (Burke 2014). With Soldiers' power requirements expecting to double by 2025 (Robyn and Marqusee 2019), this can further reduce combat range.

Given the significantly greater mass and volume specific energy of aviation fuels, it would be advantageous to utilize combustion engines. However, for engines at this size (i.e., 100-1000 W power range), heat transfer losses are noteworthy due to a greater surface area to volume ratio resulting in low thermal efficiencies (5-9% (Dunn-Rankin et al. 2006)). In addition, these relatively small-sized ICEs have noteworthy acoustic and heat/exhaust signatures that can restrict their combat readiness (Council 2004). Here, the use of AM techniques for the fabrication of ICEs utilizing materials that are resistant to heat transfer losses (e.g., titanium) can enable high engine efficiencies. Furthermore, moving from an ICE to the free-piston engine architecture offers the promises of reduced noise, fuel flexibility, and increased thermal efficiencies (e.g., (Hung and Lim 2016)). In addition, the combination of a FPE with a linear electromagnetic generator facilitates recharging of a battery bank to be utilized during silent watch.

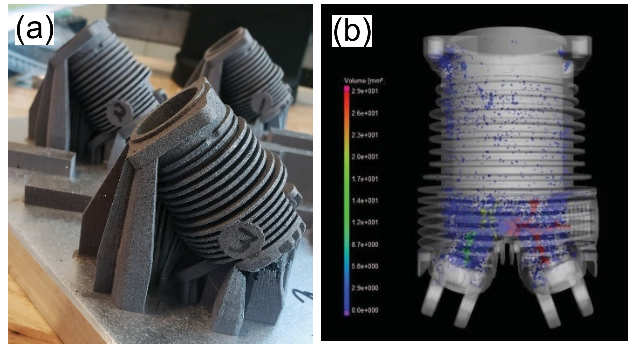


Figure 3. Aluminum engine cylinder head (a) fabricated using 3-D printing and (b) porosity characterized using a CT scan by our team members at ARL.

**As a result, this platform can support the P&E requirements for the Army of the future.** Currently, only one other entity has constructed and tested a combustion engine using AM (Kass et al. 2014); whereas, no research can be found regarding FPEs built in this manner. Our group is pioneering research in this area through the construction of a four-stroke UAS-capable 735 W ICE (total envelope volume: 0.744 L) with the crankcase and cylinder head constructed using titanium (Ti-6Al-4V) and aluminum (AlSi12) on 3D Systems 320 and 300 machines, respectively. The AM crankcase had 1/34$^{th}$ the porosity average of the die cast original design; whereas, the cast cylinder head had pores that were 150× greater than the AM-constructed cylinder head (Figure 3). Overall, the AM engine utilizing the titanium crankcase and aluminum cylinder head ran without failure for over 3.5 hours during propeller and dynamometer-based testing. *Thus, AM has already proved its superiority at the TRL 4 level*.

**3. Practical P&E Technology Solution for 2035**: AM is an appealing option because of its freedom from typical manufacturing constraints and its ability to produce highly optimized designs at low weight using non-conventional powertrain materials on-location and on-demand; thereby, reducing the costs associated with supply chain and delivery and quickening the fabrication time (Gao et al. 2015). The use of AM has the potential to increase reliability, improve performance, and minimize the number of parts. However, with machine and materials costs ranging from 50-90% of the total cost (Thomas 2013), use of AM is more competitive for lower volume productions. In addition, AM is an ideal target through cyber- and cyber-physical attacks, theft of technical data, and manufacture of export-controlled items; hence, security gaps in the process chain must be identified and removed (Yampolskiy et al. 2017).

Regarding the future use of AM for combustion engines, it eliminates the expensive and complex casting process required while achieving a greater level of control and fidelity. Furthermore, AM will decrease the need for storage of spare parts, molds, and dies if something breaks. This can diminish lead times and create a faster return to the field since AM fabricates at the point of need. This is particularly advantageous for the military given the respectively low quantities of power plants required in comparison to commercial applications. In addition, the AM process is scalable; i.e., it is feasible to move directly from an 11 cc cylinder head (Figure 3) to a 600 cc cylinder head given the build envelope is large enough, and with better relative tolerances. However, the physical act of printing the parts is just the first step, and roughly only 20% of the actual process. The AM parts require powder removal, stress relief, removal from build plates (and re-facing the plates), full heat treatment to convert microstructure to as-desired, inspection and final machining of mating surfaces, etc. These additional ~80% of the process steps need to be factored into forward-deployed AM manufacturing at the point of need considerations.

Lastly, existing parts can be redesigned for enhanced reliability and durability to take advantage of the AM process. For example: (1) Hollow wall crankcases can be fabricated using higher strength to weight ratio materials while improving cooling and rigidity; (2) Cooling fin re-design (e.g., beehive inspired) can provide an increased heat transfer rate; (3) Intake systems can be optimized to generate turbulence to facilitate a quicker and more thermally efficient combustion process; (4) Metal propellers can be made thinner and more efficient, improving thrust and reducing UAS noise; and (5) Structure integrated mufflers, unique internal geometries, and heat dissipators can decrease acoustic and infrared signatures along with vibrations (Schrader et al. 2019). Perhaps what is most exciting in this area is the linkage of finite element analysis, computational fluid dynamics including combustion predictions, and optimization software programs in the topology optimization of engine parts to improve heat transfer characteristics while reducing mass (Gray 2020). Combining these tools with the rapidly evolving technology of Artificial Intelligence will result in a dramatic re-design of the engine as computer algorithms will work to maximize efficiency and durability while minimizing weight. This will significantly advance the specific energy and power output of combustion engines by 2035.

*3.1 Next-Generation Free Piston Engine-Linear Generators*: To meet future power requirements of the US military, a recent study showed that FPE-LG technology is more suitable where lightweight and low cost manufacturing capabilities are paramount (Depcik et al. 2020). Overall, a FPE has numerous advantages over traditional reciprocating systems – namely a variable compression ratio that allows for fuel flexibility along with an easier integration with hybrid technology. Moreover, its simplified design with potentially fewer components can increase the power-to-weight ratio while reducing frictional losses, subsequently boosting engine efficiency (Preetham, Anderson, and Richards 2012). Most efforts in the development of FPE technology have been conducted on the macro-scale to yield multiple kW levels of output power (Jia et al. 2016). However, free-piston based architectures are being studied at reduced length scales suitable for small UAS and Soldier power (Aichlmayr, Kittelson, and Zachariah 2002). At present, the acoustic signature of ICE-based UAS for the US military are audible on the ground as an incessant hum – a major concern (Rempfer 2018). Here, since a FPE operates at a respectively lower and nearer to constant

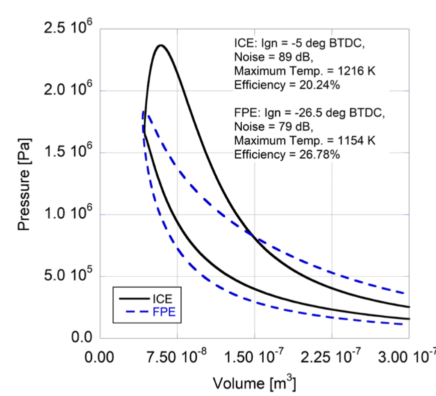

Figure 4. Using our preliminary work that captures the low-pressure operation of a FPE in comparison to an ICE to determine the potential of a future FPE operating at 70 W (power at maximum UAS speed).

pressure design (Figure 4), there is a greater potential to mitigate its acoustic signature. In addition, the hybrid-enabling technology of the FPE-LG can ensure battery re-charging prior to entering silent watch. Therefore, FPE-LG offers an alternative engine technology with high-energy density, lightweight, and low heat and acoustic signatures.

*3.2 2035 Projection:* To understand the potential of a FPE-LG for 2035, the model in (Depcik et al. 2020) for the most abundant military UAS was converted to run on Jet-A as the fuel. This UAS requires around 70 W to fly at maximum speed with the current generation of Li-ion battery technology only able to operate for around 50 minutes. As FPE-LG technology continues to improve, it is expected that AM can enable small four-stroke designs while reducing heat transfer losses by 2×. Using the model to scale the FPE-LG to reach the 250 W motor power currently employed in this UAS finds that it will only be 0.237 L in total envelope size with a mass of 0.199 kg; hence, an extremely portable design at 1.056 kW/L and 1.257 kW/kg. Moreover, performing a combustion timing optimization finds that at maximum flight speed, the FPE-LG will be able to run for 9.8 days based on only 0.4 kg of fuel (effectively equivalent to the hydrogen tank mass used in (Depcik et al. 2020)). Simulating the combustion noise (Shahlari et al. 2015) (not including dampening by the case) finds that a FPE will be an estimated 10 dB quieter than a corresponding ICE at a respectively high thermal efficiency of nearly 27% (tripling the previous best ICEs at this scale). Finally, since the FPE operates at a lower pressure, and therefore temperature, it will generate fewer problematic species like nitrogen oxides.

**4. Cross-Functional Team (CFT)**: To achieve an AM-constructed FPE-LG that effectively supports the Army MDO in the 2035 environment requires a CFT that bridges the gaps between academia, industry, manufacturing, and government laboratories. First, combustion experts are required who understand the fundamentals involved with the conversion of both conventional and alternative fuels to heat and subsequent power. More specifically, this includes linking the chemical make-up of the fuels (e.g., density, viscosity, energy content) to the fuel injection (i.e., atomization and vaporization) and chemical breakdown processes within the engine. For 150 years, the ICE has been designed for petroleum fuels and the geometric limitation of the crankshaft assembly. Therefore, combining fuel knowledge with an understanding of the unconstrained FPE combustion process is needed to change the template of engine design. This will lead into the minimization of fuel usage and weight while enabling fuel flexibility; hence, a greater endurance for UAS and larger combat range for Soldiers. These experts must understand policy and regulatory concerns and how future fuels in combination with a FPE can be co-optimized to mitigate hazardous and greenhouse gas emissions.

Second, control systems experts are needed to develop methods to prevent the collision of the piston with the cylinder head. Furthermore, new sensing and control strategies are necessary to ensure the FPE is operating at its optimal performance point. This includes integration with other electronics to prevent signal noise contamination while ensuring sufficient battery pack re-charging in a hybrid powertrain. Third, material and thermal experts are required to investigate and develop new materials that are heat and high stress tolerant. This includes consideration of the potential health and safety implications that exposure to these materials might incur for workers (Roth et al. 2019). These specialists must design printing approaches and optimization algorithms that produce high dimensional accuracy, superior surface quality, and extremely durable parts while reducing the number of support structures and post-processing machining steps. Here, established companies (e.g., Aerojet Rocketdyne) with vast experience in developing alloys (e.g., IN718, Inco 625, and Haynes 230) for high-temperature applications (e.g., Hypersonic air-breathing scramjet engines) must be involved for military-grade applications.

Fourth, industry partners must be involved to ensure that the designs consider weight and volume and can fit into the proper P&E platform. Their involvement also facilitates checks and balances on the research and development process by helping translate the findings into commercial products. These partners must collaborate with machining companies who can provide feedback on the ~80% of the process steps and filter the findings upstream to reduce the time, cost, and expenditure of creating production-ready parts. Captured within this process is the need for training at community and technical colleges along with universities to create a viable pathway for student and worker development (Huang and Leu 2014). Finally, Government partners are needed to execute the modernization of facilities and work with the team on minimizing the overall investment and unit cost for the Army. This includes translating academic research findings to a practical outcome by vetting through the industry partners to generate P&E technologies that enhance Solider and UAS range.

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