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ADVANCED POWERTRAIN DEMONSTRATOR (APD) INTEGRATION

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ABSTRACT

Evolving requirements for combat vehicles to provide increased mission capability and/or crew safety necessitate the addition of components and add-on armor to currently-fielded vehicles. These new requirements result in increased weight and increased electrical needs, which result in reduced mobility. The APD is built from the ground up to optimize a powertrain solution using cutting-edge technology specifically designed for harsh military environments, for use in both vehicle retrofits and new vehicle designs. The APD combines an efficient 1000 hp engine, transmission, integrated starter generator, thermal management system, and lithium-ion batteries to maximize powerpack power density. The APD was designed for a 45-60 ton combat vehicle, but designing for scalability, reconfigurability, and using modern techniques and technology has allowed the APD to greatly improve the capability and flexibility of the powerpack and the technology can be applied to heavier or lighter vehicles.

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1.0 Introduction

Military combat and tracked vehicles are required to operate in a range of harsh environments and perform unique tasks that differ from conventional commercial conditions. Powerpack components must be reliable, easy to operate, and capable of enabling a wide range of systems to maximize vehicle capability. This paper describes the advantages and methods of focusing on the development and integration of military-specific powerpacks using modern solutions. The following sections will discuss the historical methods for implementing new powerpacks into military vehicles, the advantages of designing and implementing a military-specific solution, and the methods employed under the Advanced Powertrain Demonstrator (APD) project.

2.0 Historical Method

Most current combat vehicles were designed using technologies from 50+ years ago. When the powerpacks were developed, commercial off-the-shelf (COTS) components were used and modified to meet the military requirements. Within the last 35 years, there has been significant divergence between commercial and military needs. Continuing to rely on COTS components that are readily available and cheaper has resulted in sub-optimized military powerpacks. A modern development with a military focus is needed to optimize vehicle powerpacks for the unique combat application.

Currently-fielded military vehicles receive incremental powerpack upgrades primarily to accommodate vehicle weight increases which are due to add-on armor. This results in sub-optimization of the powerpacks and often leads to trade-offs in mobility, reliability, and durability. Commercial solutions focus on specific capabilities and requirements that are only a subset of military requirements and rarely meet the unique configurations of military vehicles. Commercially-developed components cannot withstand the harsh military environments, which include extreme hot and cold temperatures, military specification fuels, dusty environments, and shock and vibration requirements.

When a modification to a vehicle is identified, which is generally performed to add safety or a new capability, the identification of impacts to the current vehicle is usually limited to the changes that must be performed to incorporate the modification. Impacts to mobility, reliability, or durability are often given only secondary consideration. However, as more and more incremental changes are made, the combined impacts become substantial, but the larger effort needed to fix the mobility degradation is out-of-scope of the modification.

“Add-on Kits” are a common way to offer a new capability or safety feature to a combat vehicle. Identifying the capability or feature as a “Kit” implies there is no impact to the current vehicle capability or performance. However, when add-on kits are needed, weight is increased, and durability and reliability are decreased, which leads to mobility trade-offs because the powerpacks are now underpowered. This, in turn, leads to minimal powerpack upgrades, which are suboptimal because these components are patched to meet the new requirements instead of being optimally designed for the new requirements.

Because military-specific technology is not a high production need, the technology does not advance at the rate that commercial technology does. Commercial technology has a much larger consumer base and is able to benefit from a larger economy of scale. Military applications try to leverage commercial components as much as possible, but diverging needs between military and commercial applications leads to suboptimal results. Commercial components are designed to operate in a much narrower range of application than military components and also have regulations that influence their design. Military components have specific harsh environment requirements and when designing for military environments the best solution is not to start with a commercial component for most cases.

3.0 Military-Specific Solution

The military powerpack customer base has needs that differ vastly from their commercial counterparts. Military-specific solutions need to be power dense in order to maximize capability, as total vehicle volume is limited and there are competing volume allocations for mission essential components. In military ground vehicles, powerpack volume also drives overall system weight due to armor requirements, placing a premium on under-armor volume. A volumetric power dense solution is therefore desired. An efficient system (more power in the same volume) allows the vehicle designer to spend more of the limited vehicle space and weight budget on mission capability and armor protection. Power density at the sprocket, as defined in [1], is a measurement of overall powertrain efficiency, and accounts for the efficiencies and parasitic burdens of supporting systems, as well as total driveline efficiency.

Both wheeled and tracked combat vehicles require ballistic grilles to protect powertrain components from external threats. These ballistic grilles are very restrictive to air flow, and due to protection requirements, there is no possibility of ram air cooling. This means that military powerpacks have to pay a heavy penalty for pulling the cooling air through these grilles. The power required to run the cooling fans detracts from the available power left to move the vehicle. This makes powerpack efficiency a key design parameter. More efficient powerpacks have less heat rejection and require less cooling fan power, so the powerpack saves fuel twice - once by being more efficient, and again by not needing to waste as much power on cooling fans. This leaves significantly more power available for vehicle mobility and vehicle-mounted electrical systems.

Still, as the largest auxiliary powerpack load, the main cooling fan is a critical focus on a military powerpack. Providing the required airflow at high pressure rise often requires an application-specific fan design, as well as attention to fan control strategy. Historically, mechanical fan drive solutions on military vehicles were designed to provide the required fan speed for worst-case conditions, but resulted in wasted fan power during most of the vehicle operating life. Newer strategies of fan control with hydraulic or electric fan motors allow for the fan speed to be controlled based on cooling needs to minimize fan load and increase powertrain efficiency across the operating range.

Modularity and applicability to different-size combat vehicles are important to increase the commonality of parts across the fleet. This will reduce the military logistical burden by reducing the number and type of parts that are needed to hold and transport as spares, resulting in fewer transport vehicles. Reducing the logistics burden results in fuel savings, lessens the number of trips or vehicles traveling to forward operating bases, and reduces the number of soldiers required to meet mission objectives. Scalability and commonality of parts across vehicles allow common parts to be produced on the same manufacturing line, which creates an economy of scale and reduces part costs and manufacturing line setup costs.

Military-specific powerpacks need to enable future capabilities required by a modern military force. These future capabilities include high power systems such as high power electromagnetic (EM) guns, active protection systems, high power detection systems, and laser weapon systems, as well as a need for improved silent watch performance. Military powerpacks do not have the luxury of operating on specialized high quality fuels available for commercial applications. Military powerpacks must be able to operate on a wide variety of fuels to reduce military logistic burdens and to accommodate limited fuel sources available in combat theaters.

The Advanced Integrated Propulsion Systems (AIPS) program, described in [2], followed this methodology of designing a complete mobility solution and became a guide and reference to developing military-centric solutions. The AIPS was designed specifically for the rear compartment of a Main Battle Tank (MBT), and was cancelled when the Army priorities changed. Following a similar approach of designing a combat system from the ground up, but designing scalability, reconfigurability, and using modern techniques and technology, has allowed the APD to greatly improve the capability and flexibility of the powerpack.

4.0 Advanced Powertrain Demonstrator (APD) Project

The purpose of the APD was to design, build, deliver, and test a state-of-the-art powerpack specifically targeting medium weight tracked combat vehicles (45-60 ton). Although a medium weight combat vehicle was chosen for the initial demonstration, the components are designed to be modular and scalable, and the technology is capable of operation in light combat vehicles or heavy tanks. A Bradley Fighting Vehicle (BFV) hull was chosen for the initial demonstration due to having one of the smallest engine compartments among current medium weight combat vehicles. The powerpack integration was designed to be a field-replaceable solution to minimize retrofit costs. The external interfaces of the hull have not been changed (to include air intake and exhaust grilles), and only minor changes are needed to the interior of the engine compartment. The APD could reduce overall logistics burdens by lowering vehicle fuel consumption and increasing part commonality across the fleet. The APD could also enable greater vehicle capability by increasing on-board or export power generation by 10x over legacy platforms to 160 kW. The objective of the APD is to significantly increase the power density and capability of medium combat vehicles while minimizing the changes to those vehicles. This is accomplished by designing compact and efficient components using modern technologies and techniques that can take advantage of the limited engine compartment within existing combat vehicle platforms, and enable better overall vehicle designs in future vehicles.

The APD consists of the Cummins 1000 horsepower (hp) Advanced Combat Engine (ACE), the SAPA ACT 1000 Advanced Combat Transmission (ACT), the L3 Communications 160 kW high voltage Integrated Starter Generator (ISG), the General Electric (GE) Integrated Starter Generator Controller (ISGC), a Marvin Land Systems electric cooling fan with optimized Boyd-Aavid heat exchanger and thermal system, the Generation-II Advanced Li-Ion Modular Batteries (AMB), Government-developed controller hardware and component software, a new self-cleaning air filtration system from Donaldson, and a custom muffler and exhaust system from Great Lakes Sound & Vibration, all integrated into a Bradley hull and tested through a Technology Readiness Level 6 (TRL 6) 75-hour dynamometer test. Figure 1 shows the integrated solution in a Bradley hull.

The 1000 hp APD utilizes the same space claim as the current 675 hp unit, uses that power more efficiently, and is able to cool it in extreme 120 °F environments, which the current pack has issues with for extended durations.

Figure 1. APD Components integrated into a Bradley Fighting Vehicle hull

4.1 **Advanced Combat Engine (ACE)**

The ACE, or Advanced Combat Engine, was designed from the ground up specifically for the demanding requirements of a combat military engine. The ACE was designed to maximize the available power in the smallest possible space claim while also minimizing heat rejection. Minimizing heat rejection is critical since it minimizes cooling fan power loads and cooling system size. Cooling fan power can approach 20% of the gross engine power in military combat vehicles due to the highly restrictive ballistic grilles and the heat exchanger air side pressure drops associated with compact cooling systems. Since cooling fan power has a cubic relationship with airflow, and air flow is directly proportional to heat rejection, a 25% reduction in heat rejection can lead to a 60% reduction in cooling fan power.

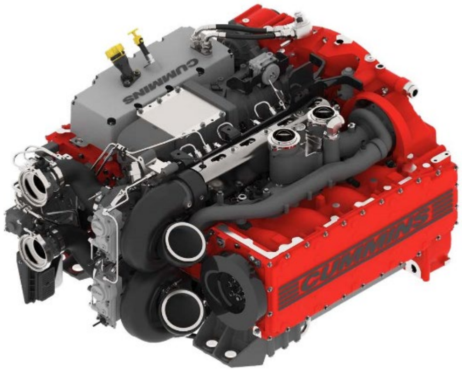

Figure 2. The Advanced Combat Engine (ACE)

The ACE was designed around the opposed-piston two-stroke (OP2S) engine architecture and is described in [3]. An image of the ACE is shown in Figure 2. Being a two-stroke engine, the engine makes power on every other stroke of the piston instead of every fourth stroke, as on conventional four-stroke engines. The piston of the four-stroke engine makes four motions, or strokes, each time it delivers power to the crankshaft. The first stroke is dedicated to bringing fresh air into the cylinder, the second stroke compresses that air in preparation for fuel injection, the third stroke is the power stroke which produces useful power, and the fourth stroke is dedicated to pushing the exhaust gasses out of the cylinder. With the two-stroke engine, the intake and exhaust processes are combined into the compression and power strokes. As a result, a two-stroke engine has the ability to make up to twice as much power as a similarly sized four-stroke engine operating at the same speed. This attribute of the two-stroke engine was essential in maximizing the amount of power available in a given space claim. As an example, the four-cylinder ACE engine has four power events per crankshaft rotation. The legacy BFV engine also has four power events per crankshaft rotation, but requires 8 cylinders to do this instead of 4 cylinders.

In addition, the four-stroke engine must control the fresh air flow into the cylinder and the exhaust flow out of the cylinder using valves. These valves must be opened and closed at the proper time in sync with the piston motion. This valve motion is obtained by linking the valves to rocker arms which follow carefully shaped cams mounted on a rotating camshaft. Each valve requires a spring and valve stem seal. The camshafts are rotated in sync with the crankshaft (timed) through a timing chain or through gears. The valve system of a four-stroke engine adds significant complexity, part count, and manufacturing cost to the engine. As an example, the legacy Cummins VT-903 four-stroke engine used in the BFV has 32 valves, 32 valve seats, 32 valve stem seals, 32 valve springs, 16 pushrods, 16 hydraulic lash adjusters,16 rocker arms, one camshaft, two timing chain sprockets, and one timing chain, all devoted just to opening and closing these valves.

The two-stroke engine accomplishes the same task by using passive inlet and exhaust ports located in the sides of the cylinder walls. These ports are exposed or occluded by the pistons as the pistons traverse the cylinder as in Figure 3. This allows the piston to perform the task of delivering power to the crankshaft and controlling the air and exhaust flows in and out of the engine without any additional parts. This makes the two-stroke engine lighter and less expensive than a comparably sized four-stroke engine.

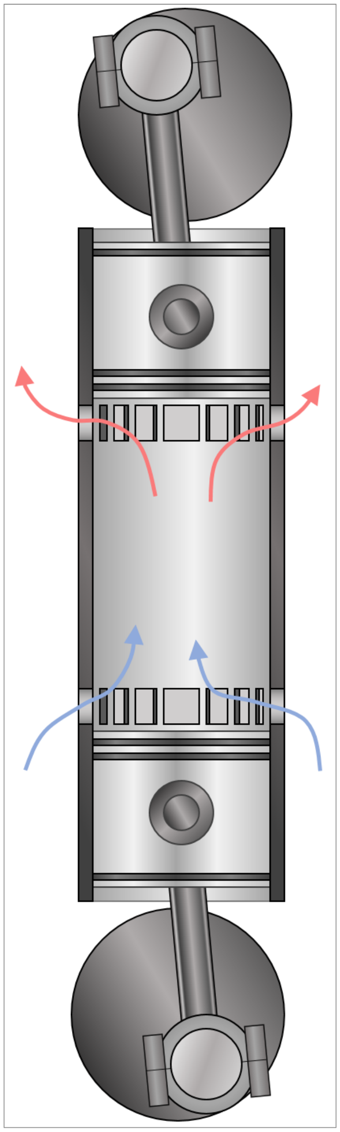

Figure 3. Two-stroke opposed piston cylinder

The architecture of the two-stroke engine when compared to a four-stroke engine allows the two-stroke engine to make more power for a given displacement with fewer parts. As a result, compared to the legacy VT-903, the ACE produces 48% more power and 87% more torque with the same engine displacement (approximately 14.5L). Yet, the ACE engine space claim is 11% smaller.

Two-stroke technology is nothing new, but the ACE is not an ordinary two-stroke engine. Traditional engines have one piston per cylinder. The bottom of the cylinder is open to the crankcase and the top of the cylinder is sealed with the cylinder head. The cylinder head holds the fuel injector and forms the upper half of the combustion chamber. This cylinder head is exposed to the high temperature gases present during combustion. In order to maintain the cylinder head at a safe temperature, the cylinder head must be continuously cooled with engine coolant. This means that a significant portion of the chemical energy released by the combustion of the fuel is being delivered directly to the engine coolant as opposed to performing useful work on the crankshaft. This lost energy ends up as engine heat rejection that must be rejected out of the vehicle through the engine cooling system. This requires large cooling fans and large heat exchangers. These large cooling fans must be engine driven which reduces the power available for moving the vehicle and power available for vehicle weapon, computer, and communication systems.

In contrast, the ACE makes use of opposed pistons as in Figure 3. This means that each cylinder has two pistons facing each other - there is no cylinder head. The pistons themselves form the combustion chamber. The pistons move towards and away from each other in sync through the use of two separate crankshafts and a series of gears between them on the power take-off end of the engine. These gears are also used to drive the engine coolant and oil pumps. In addition, these gears allow the engine output shaft to operate at a speed other than the crankshaft speed. This results in application flexibility by allowing the engine speed range to be adjusted to match the needs of a particular transmission or application. Also, by allowing the crankshaft to spin slower than the output shaft, the engine can minimize the frictional power lost to piston and crankshaft motion.

The real benefit, however, comes from the elimination of the cylinder head. As pointed out previously, since the cylinder head is directly exposed to the combustion gasses and must be cooled, it acts as a major contributor to engine heat rejection. By eliminating the cylinder head, the energy lost from the combustion gasses to the environment can be minimized, reducing the heat rejection from the engine. Each piston is left to reject about the same amount of heat as it had to reject previously. However, it is not as easy for the OP2S piston to reject that heat. In a four-stroke engine with a cylinder head, the piston gets two strokes where it is free from combustion heat loads, and during those two strokes, it has some limited opportunity to shed heat via radiation to the cylinder head. The pistons of the ACE are exposed to combustion heat on every stroke and they are exposed to a piston of the similar temperature so there is no chance of cooling the piston through radiation. This means that the ACE pistons do operate at higher temperatures than typical four-stroke pistons. This is where modern engineering processes and state-of-the-art computer simulations come in.

The ACE pistons are a two-piece design with an internal oil gallery meant for piston bowl cooling. Oil is administered to the oil gallery via oil spray nozzles which inject oil into the piston from below while the piston is near Bottom Dead Center (BDC). Cummins and its partners have been working closely together to model the oil flow through the piston as well as the heat transfer through the piston crown and into the oil. This involves computer simulations that can actually predict oil particle motion and distribution throughout the oil gallery as the piston is moving through the cylinder.

In order to provide proper water jacket cooling to the engine cylinders while minimizing engine size and weight, the ACE makes use of a parent bore cylinder supported by numerous pin shaped cooling fins. These pin fins dramatically improve the ability to maintain top dead center (TDC) cylinder wall temperatures while simultaneously providing the physical support for the cylinder wall. These pin fin supports are buried inside the center of the casting inside of the water jacket where it is impossible to introduce a sand core using traditional sand casting pattern techniques. The inclusion of these pin fins in the cylinder block has only been made possible by cutting edge 3D printer technology. The sand cores for the water jacket and cylinder structure are printed using a specialized 3D printer that can print three dimensional objects using sand held together with a binder. These 3D printed cores are then placed into the rest of the engine block mold in preparation for casting. After the engine block casting has been poured and cooled, a washing agent is sprayed through the water jacket that dissolves the 3D printed sand core binder. This allows the 3D printed cores to be washed out of the finished block without the need for freeze plugs or other access ports to remove the sand cores after casting. This cutting edge technology allows the ACE to make double use of cylinder structural elements as cooling elements, minimizing weight, package space claim, and part count, while maximizing engine block strength and reliability.

These unique features of the OP2S engine allow the ACE to operate at a significantly lower heat rejection than legacy engines in use in military vehicles. The heat rejection burden of an engine to the vehicle is typically measured in kW/kW. This is a measure of how many kW of thermal energy are released for each kW of engine power available on the crankshaft. The majority of engines used in the US Army struggle to get below 0.7 kW/kW. However, by making use of the OP2S technology, the ACE will be capable of achieving 0.55 kW/kW with plans in place to reach 0.5 kW/kW or less. This means that the ACE is capable of producing from 27% to 40% more shaft power with no increase in heat rejection or cooling fan loads. This directly impacts powerpack power density by increasing the useful power available to move the vehicle and power combat systems without increasing powerpack space claim or ballistic grille size.

There are other high power density engines available for military applications that deliver large amounts of power in fairly small package volumes and displacements. These high power density engines obtain their high specific power levels by making use of very high intake manifold pressures. These high intake manifold pressures are provided by large turbochargers that significantly increase the temperature of the incoming combustion air. This hot, compressed, combustion air must be cooled down with one or more Charge-Air Coolers (CACs). In order to meet the specific power levels, these CACs are either air-to-air, which significantly burdens the cooling system by requiring the addition of a large heat exchanger, or are air-to-liquid and require relatively cold coolant in the range of 80°C to 85°C. Obtaining coolant this cold when operating in 50°C ambient conditions places a large burden on the vehicle cooling system by requiring a large heat exchanger and large fan powers to pull the required cooling air through the ballistic grilles. In contrast, the ACE has two fully integrated CACs that are directly cooled with the core engine coolant. No additional coolant hose connections or charge-air hose connections are required. These integrated CACs, being cooled with engine coolant at 110°C, significantly reduces the cooling burden and parasitic losses at 50°C ambient conditions. This means that the ACE allows the APD to achieve higher integrated powerpack densities than any other high power density Diesel engine could support.

4.2 **Advanced Combat Transmission (ACT)**

The ACT, or Advanced Combat Transmission, was also designed from the ground up to meet the unique requirements of a tracked military combat vehicle. The technology used to build the transmission is described in [4] and [5]. The primary goal of the design was to increase efficiency while also improving vehicle performance. The ACT is shown in Figure 4. Increasing efficiency alone is very important. Transmission efficiency is a measure of how much of the engine's power makes it to the sprockets to propel the vehicle. Any power that does not make it to the sprockets is lost to heat. This heat must be rejected from the vehicle through the cooling system using engine-driven fans. As transmission efficiency is increased, the vehicle receives a twofold benefit. First, more power is available at the sprocket. Second, the heat rejection is lower, which means that the power required to drive the cooling fans goes down, which means even more power is available at the sprocket. As mentioned earlier in the paper, as vehicle platforms mature, they typically receive more armor and new combat systems which increase vehicle weight. This causes vehicle performance to suffer and it also makes the vehicle harder to steer and harder to stop. These weight increases over the decades have resulted in existing transmissions that are no longer able to provide adequate braking and steering performance, which can lead to serious safety and maneuverability issues. For this reason, the ACT was designed to provide improved braking and steering performance for vehicles up to 50 tons for the APD, with the ability to upgrade to a 60 ton brake capacity for follow-on applications with a small increase in width.


Figure 4. The Advanced Combat Transmission (ACT)

The main features of the ACT that allow it to be more efficient are the inclusion of more gears and the elimination of the torque converter. Many of the transmissions available for use in tracked combat vehicles are limited to 3 or 4 gears. This means that as you switch gears, there is a fairly large change in engine speed. Also, with only 4 gears, it becomes difficult to cover the entire range of desired vehicle speeds. This can be shown in Figure 5 and Figure 6. Figure 5 is a generic engine torque and power curve for a typical Diesel engine with 20% torque rise, which is the starting point for most engine requirements. Figure 6 shows the maximum sprocket power available from a generic four-speed transmission when coupled to this engine. For simplification, the transmission was assumed to be 100% efficient. Even with a perfect transmission with no losses, the sprocket power is not constant with speed. This is due to the shape of the engine power curve and the large changes in engine speed between gears. The average power available to the sprockets during a full throttle acceleration event is less than 80% of the rated engine power. This is attributed to the fact that the engine's rated power can only be achieved at the engine's rated speed. With a limited number of gears, just as the engine gets to rated speed, the transmission shifts to the next gear and the engine speed falls as well as engine power. Additional issues can be seen in 1st and 2nd gears. Since the vehicle needs to operate at low speeds, such as a troop march, the first gear needs to be set low enough to keep the engine speed up during these low vehicle speed events. This results in a gap between 1st and 2nd gear where very little sprocket power is available between 3 miles per hour (mph) and 5 mph. This same issue occurs at vehicle speeds less than 2 mph.

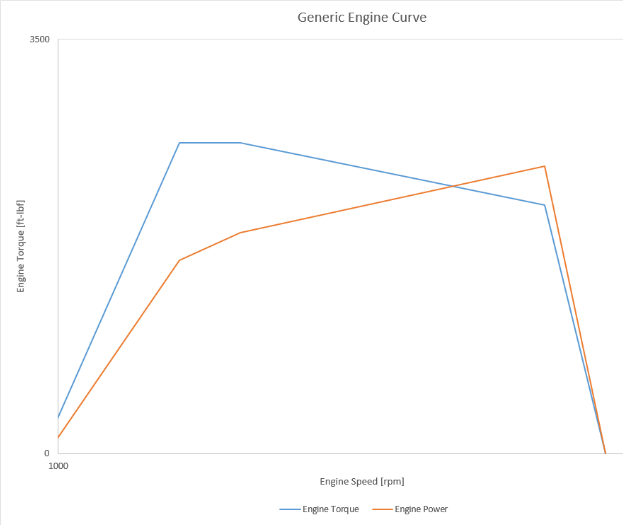

Figure 5. Generic engine torque and power curve for a typical Diesel engine with 20% torque rise

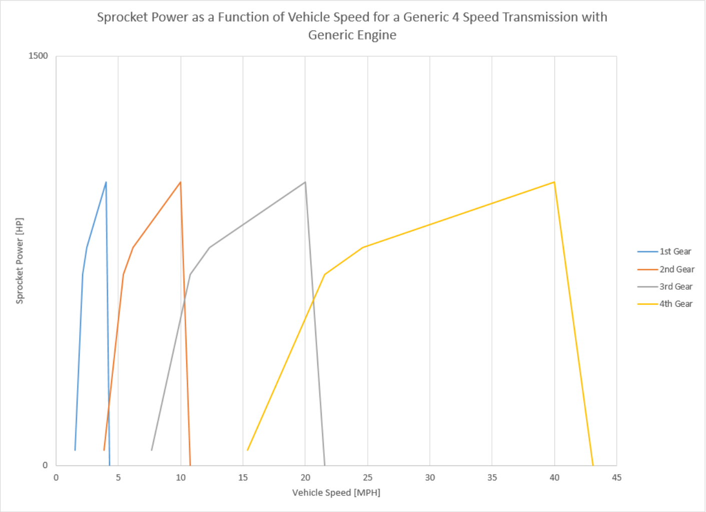

Figure 6. The maximum sprocket power available from a generic four-speed transmission

Over the years, numerous solutions have been devised to overcome these issues. The first and most common is the torque converter. The torque converter is a fluid coupling device that transmits power through oil. It consists of an impeller and turbine. The impeller is a disc with numerous vanes which is spun by the engine in an oil bath. The vanes accelerate the oil and direct the oil at high speed towards the turbine. The turbine is also a disc with numerous vanes attached to the input shaft of the transmission. As the high-speed oil strikes the vanes on the turbine, a torque is generated which forces the input shaft of the transmission to rotate. With the addition of a stator section and an overrunning clutch, the modern torque converter is capable of torque multiplication, meaning that the torque delivered to the transmission is greater than the torque from the engine. This sounds like a great solution, but nothing comes for free. The torque converter, being a fluid coupling, always slips. In other words, the turbine always spins slower than the impeller. This loss in speed shows up as loss in power, and this loss in power shows up as heat.

Transmission engineers have used torque converters to fill in the gaps in the sprocket power curve. So in the bottom end of 1st, 2nd, and sometimes 3rd gear, the torque converter becomes active. The slippage of the torque converter allows the engine to run at higher speeds then the transmission input shaft is turning. This allows the engine to speed up closer to rated power even when the vehicle is moving at slow speeds. This fills in the power gaps between gears and helps increase the average sprocket power during an acceleration run. However, there is a significant penalty for doing so, which comes in the form of heat. In many transmissions, the torque converter must be active at high tractive efforts. At these high tractive efforts, the torque converter is slipping so much that 20-25% or more of the engine power is being converted directly to heat. On a 1000 hp engine, this means that 200-250 hp is lost as heat. Since military combat vehicles must be capable of continuous operation at high tractive efforts, the cooling fans and heat exchanger must be sized to reject this large amount of heat. This is on top of other losses within the transmission. The typical tracked combat transmission struggles to achieve 85% efficiency when the torque converter is inactive and can have efficiencies as low as 60% when the torque converter is active.

Another solution to solve the performance gaps of a typical four-speed transmission is to use a hydrostatic drive Continuously Variable Transmission (CVT). The HMPT family of transmissions function as a hydrostatic CVT, especially in first gear, reverse, and pivot. A hydrostatic CVT is essentially a variable displacement hydraulic pump driven by the engine coupled to a fixed displacement hydraulic motor coupled to the transmission output shafts. The hydraulic pump pressurizes the hydraulic fluid to thousands of pounds per square inch. This hydraulic fluid, under high pressure, forces the hydraulic motors to rotate, causing the vehicle to move. Since the hydraulic pump is variable displacement, it can continuously change the speed of the sprockets even when the engine is at a fixed speed. This feature allows the engine to be held at rated engine power during the duration of the acceleration event, eliminating the drops in power experienced by the four-speed transmission. This sounds like an ideal solution until you examine the losses in the system. The hydraulic pumps and motors suffer from both mechanical inefficiencies due to friction and volumetric inefficiencies due to fluid leakage past the pistons. The typical hydraulic pump might have a mechanical efficiency of 96% and a volumetric efficiency of 94%, resulting in a combined efficiency of about 90%. The hydraulic motors have a similar efficiency. This leads to an overall transmission efficiency of just 81%, which is worse than the four-speed transmission. Volumetric efficiency is due to leakage, which is directly related to pressure and fluid viscosity. At high tractive efforts, the hydraulic pump reaches maximum operating pressures. This causes an increase in leakage and a drop in volumetric efficiency. As the hydraulic pressure leaks past the pistons from a high pressure to a lower pressure, energy is released in the form of heat. This heat causes the hydraulic fluid temperature to increase. As the hydraulic fluid gets hotter, its viscosity decreases and the leakage gets worse. As this occurs, this style of transmission can enter a thermal runaway, where high tractive efforts cause low efficiencies, which cause high fluid temperatures, which cause even lower efficiencies and even hotter fluid. The spiral continues as the vehicle speed drops to very low levels. Overall efficiencies can fall below 60%. If the driver does not pull back on throttle, the fluid viscosities will get so low that the hydraulic pump and motor lubrication will suffer causing catastrophic damage to the components.

The ACT found a much better solution by adding more gears. The ACT has 32 forward gears and 32 reverse gears. This means that the change in engine speed going from one gear to the next is quite small. This allows the sprocket power to remain high during an acceleration event by maintaining the engine speed at or very close to rated engine speed and maximum engine power. In the example shown in Figure 7, the engine is capable of delivering an average of 96% of rated engine power over an entire acceleration event as compared to 80% for the four-speed transmission shown in Figure 6. Also, since the gears are very close together, there are no gaps between gears that need to be filled in with a torque converter. Since there are so many gears so closely spaced, it almost appears that the transmission is continuously variable. The gear coverage is also broad enough to accomplish high tractive effort operation at low speed in gear without using a torque converter. This provides the user with the best of both worlds - a transmission without the need for a torque converter, but with the operational characteristics of a hydraulic CVT without any of the associated losses. Using this technology, the ACT is able to achieve efficiencies greater than 90% in all gears at all loads, with peak efficiencies reaching 95%. With traditional transmissions, the cooling system must be sized for high tractive efforts. This means that the ACT is capable of operating at high tractive efforts at 90+% efficiency, while the four-speed transmission and the hydraulic CVT efficiencies fall below 70% to as low as 60%. This means that the ACT produces less than 1/3 of the heat, that the transmission cooler can be 1/3 the size, and that the cooling fans can be significantly smaller. This makes a significant contribution to powerpack power density. This increase in transmission efficiency, along with less heat rejection from the engine, allows the APD to produce 67% more sprocket power in the same space claim with no changes to the ballistic grilles. This is a first in combat powerpack development.

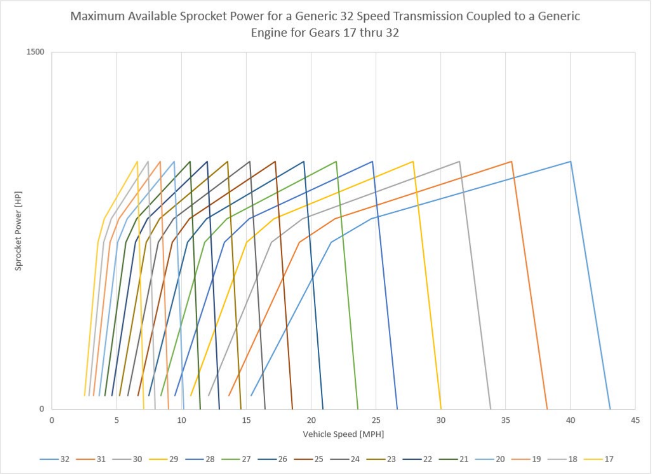

Figure 7. Sprocket power of a generic 32-speed transmission

The ACT was also designed to improve vehicle steering and braking performance. All tracked combat vehicle transmissions must find a way to make one sprocket turn faster than the other to steer the vehicle. In the past this was done by applying a brake to the inside sprocket to slow it down, but this wastes power and slows the vehicle down. All modern transmissions use a form of hydraulic CVT to force one sprocket faster while slowing the other sprocket down. The advantage of these systems is that as the inside track is slowed down, mechanical power is absorbed and transferred to the outside track. This allows the vehicle to maintain speed through turns with less power from the engine. However, there is an inefficiency involved with this process. As mentioned before, the hydraulic CVT will have a best case efficiency of about 81%.

The ACT, instead of using a hydraulic CVT to induce differential sprocket speeds, makes use of a second, fully-integrated 32-speed steer transmission. So the ACT is actually two 32-speed transmissions in one.

One larger 32-speed transmission handles the primary propulsion loads and allows for 32 forward gears and 32 reverse gears. Meanwhile, a second, smaller 32-speed transmission is used to induce differential sprocket speeds resulting in 32 different possible steering radius options to the right and 32 different possible steering radius options to the left. Since there are so many gears, and the speed changes are so small between the gears, the driver is unaware of the gears. The driver only feels a smooth variation in vehicle steering from left to right. Since the ACT relies on a 32-speed steering transmission operating at 90% efficiency as opposed to a hydraulic CVT operating at 81% efficiency, steering losses and the associated heat due to these steering losses will be cut by 47%. This minimizes engine make-up power, and allows the vehicle to travel faster through turns, improving its maneuverability, while also reducing the heat that must be rejected from the vehicle.

Most combat transmissions either have wet brakes or dry brakes. Each has its benefits and weaknesses. Wet brakes are ideal for sustained downhill grades since the brakes are continuously cooled with transmission oil. This prevents brake fade, which is the result of brake friction material heating up over the duration of a braking event. As the brake friction material heats up, its coefficient of friction drops, and the vehicle stopping power fades away. On sustained downhill grades, this can lead to a runaway vehicle. With the constant cooling provided by the transmission oil, the brake friction material temperature can be maintained at a constant value and brake fade can be avoided.

Unfortunately, wet brakes are not as good at handling panic braking events. During a high-g panic braking event, an enormous amount of energy must be absorbed through the sprockets and dissipated in the brakes. This sudden influx of energy can cause wet brakes to heat up very quickly. If the brake temperature exceeds the maximum oil temperature, the oil will coke. This degradation to the oil will cause other problems in the transmission since this is the same oil that is used to lubricate and control the transmission. The long-standing solution has been to make wet brakes larger and heavier than they need to be so that the thermal mass of the brakes can absorb the energy without overheating the oil.

Dry brakes are excellent at handling panic braking events. Dry brakes have the brake rotor and friction material exposed to the engine compartment air. They do not have to worry about overheating the oil, so they can handle very large influxes of energy without an issue. However, they do suffer from brake fade on long downhill runs and reduced stopping power when wet from a fording event.

The ACT was designed with both dry and wet brakes, which, again, results in the best of both worlds. The brake pedal position is sent to the transmission controller which splits the braking effort between the wet and dry brakes based on the type of braking event and pedal force. For long-duration downhill grades, the wet brakes come into play to avoid brake fade. When brake pedal forces are high, such as in high-g panic braking events, a majority of the braking effort is taken up by the dry brakes to avoid overheating the transmission oil. The result is that the wet brakes no longer have to be oversized in order to provide thermal mass for panic braking events and the dry brakes no longer have to be oversized to avoid brake fade on long downhill descents. This results in a smaller, lighter transmission with less heat rejection to the transmission oil cooler while providing superior braking performance.

The ACT, being designed from the ground up for modern military applications, is also fully electronic. Being fully electronic, it is drive-by-wire and ready for use in remote controlled and autonomous vehicles without any modifications. It can also be used in applications with more than one driver's station where control of the transmission can be switched seamlessly from one crew member to another. For safety critical applications that still desire mechanical control linkages, mechanical controls for both steering and parking brake can be used with very minor modifications.

4.3 **Integrated Starter Generator (ISG)**

The APD incorporates an Integrated Starter Generator or ISG. As the name implies, this device is used as the primary means to start the engine and provides 160 kW of electrical power to the vehicle. The ISG, designed and built by L3 Communications – Magnet Motor, operates at High Voltage (HV) and couples directly with the Integrated Starter Generator Controller or ISGC. The ISG mounted on a dynamometer is shown in Figure 8. The ISGC was designed and built by General Electric Aviation Systems under the direction of Ground Vehicle System Center (GVSC). The ISGC is used to couple the variable-voltage and variable-frequency electrical output of the ISG with the APD's 600 Vdc bus. The vehicle does not require a 600 Vdc bus to make use of the ISG and ISGC. The APD, as integrated into a BFV, integrates with the vehicle's existing low voltage (LV) 28 Vdc bus through bi-directional DC-to-DC power converters that can convert HV to LV and LV to HV. When starting, LV power is drawn off of the vehicle's 28 Vdc battery system and is converted to 600 Vdc by the bi-directional DC-to-DC converters. The ISGC draws power from the 600 Vdc bus and converts it to three-phase power required to start the engine. Once the engine has started, the ISGC starts treating the ISG as a generator. In the generating mode, the ISGC draws three-phase variable-voltage and variable-frequency power from the ISG and converts it to 600 Vdc power. This 600 Vdc power is made available for the APD main cooling fan and to the bi-directional converters. The bi-directional DC-to-DC converters convert a portion of the 600 Vdc power to 28 Vdc to recharge the vehicle batteries and to power 28 Vdc vehicle systems.

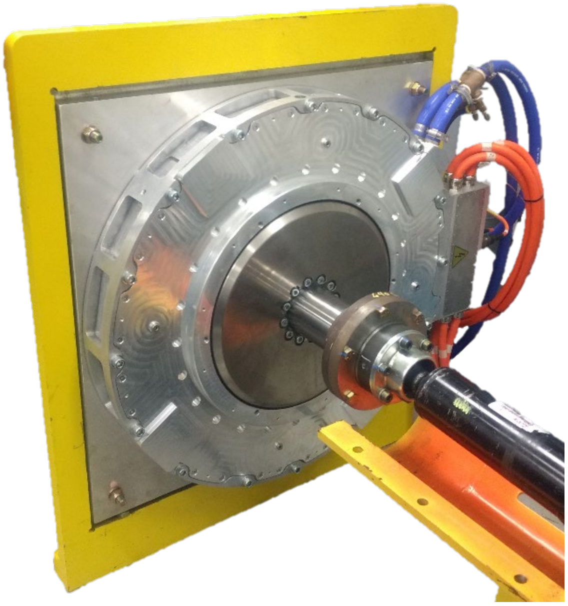

Figure 8. ISG installed in a test cell

The ISG and ISGC system were designed from the ground up to maximize powerpack density. As with the other components discussed, this is best done by minimizing package space claim, maximizing efficiency, and minimizing cooling burden.

The ISG was designed to integrate between the engine and the transmission. Normally, electrical generators are made smaller for a given power rating by making them spin at higher speeds. This option was looked at early on for APD. The disadvantage of high-speed generators is the need to provide a high-speed Power Take-Off (PTO) gear box system to spin the high speed generator with the relatively low-speed engine. Oil distribution, bearing lubrication, gear tooth meshing action, and system vibrations all become more difficult on high-speed gearboxes. For these reasons, high-speed gearboxes need high precision bearings and very precise gears, which adds cost to the system. The high-speed gearbox would also need to deal with a very challenging torsional vibration environment since it needs to transfer power between the torsionally-active engine and the high-inertia of the high-speed generator.

By designing the ISG to be a low-speed machine spun directly from the crankshaft, many of these issues were completely eliminated. The ISG only has one moving part. The ISG does not have any bearings, brushes, or wearable parts. The ISG rotor is bolted directly to the transmission input shaft and the ISG stator is bolted directly to the transmission. In this way, the transmission input shaft bearings support the ISG rotor with no additional burden to the powerpack. The ISG requires no lubrication and has no periodic maintenance tasks associated with it. The ISG stator housing takes the place of the engine flywheel housing and is used to join the engine to the transmission. In this way, the ISG takes no additional space on the powerpack. In fact, if the ISG were removed from the powerpack, the powerpack would still be the same size. This is due to the fact that a torsional coupler (spring disk) must be present between the engine and transmission, just as on the VT-903 engine today. This torsional coupling is packaged inside the center of the ISG is just long enough to house the torsional coupling. If the ISG was removed, a flywheel housing of the same length would still be needed in order to house the torsional coupling. So 160 kW of electrical power was made available, without increasing the size of the powerpack, while also freeing up the space which would normally be used by the engine starter motor, high-speed low-voltage generator, and high-speed PTO gearbox.

In order to maximize power output while minimizing thermal burden, a permanent magnet architecture was chosen for the ISG. By using permanent magnets in place of the wound-field architecture common on high-speed low-voltage generators, the parasitic losses required to support the field current were eliminated. This, along with the fact that the ISG has no bearings and no frictional losses other than air windage, allows the ISG to be significantly more efficient than the typical high-speed low-voltage generators used today. In fact, the ISG is over 96% efficient across its entire operating envelope.

It takes more than just reducing heat rejection to minimize the thermal burden. Modern commercial hybrid-electric technology, such as permanent magnet motor/generators and controllers, typically require fairly cold coolant temperatures, in the range of 70°C to 80°C. These coolant temperatures can be very hard to achieve in desert combat conditions when it is 50°C outside and the air flowing into the heat exchangers can reach 55°C to 58°C. The small temperature delta between the required coolant temperature and the incoming air mandates large heat exchangers and large amounts of air flow requiring large ballistic grilles and high cooling fan powers. Since the ISG and ISGC were being designed from the ground up for use in military combat vehicles, GVSC mandated 105°C coolant temperatures for both the ISG and the ISGC.

In order to meet this stringent temperature requirement, a new rotor architecture and magnet mounting system was developed to minimize internal rotor losses that could threaten demagnetization. With this new architecture, the ISG has successfully demonstrated the ability to operate at continuous electrical loads in excess of 160 kW, at engine compartment temperatures, with 105°C coolant, with no degradation.

The ISGC makes use of Silicon Carbide switching transistors to meet the 105°C coolant requirement. The switching transistors used in generator and motor controllers are constantly switching from their OFF state to their ON state, as they generate the Pulse Width Modulated (PWM) voltage wave form for the electric machine. The transistors make very little heat in the ON state since their internal resistance is very low. Transistors also make very little heat in the OFF state since their internal resistance is very high and electrical currents are very small. However, during the transition from the OFF state to the ON state and from the ON state back to the OFF state, the resistance must pass from near infinity to zero and back again while passing large currents. During this transition, the transistors are experiencing I^2R losses. This forms the major amount of heat that must be rejected from the transistor through the transistor cold plates in order to maintain the transistor junction temperature at or below its continuous operating temperature. The faster the transistor can make this transition, the less time is spent between the fully OFF state and the fully ON state, and the smaller the I^2R losses. Silicon carbide transistors have significantly faster transition times than do traditional silicon transistors. This means that the transistors spend less time between the ON state and the OFF state, which means the ISGC makes less heat than the typical commercial generator controller. This allows the ISGC to be operated at higher coolant temperatures while still maintaining safe transistor junction temperatures.

By packaging in space already needed to support other powerpack functions, by using the transmission bearing as the support for the ISG rotor, by making use of an advanced high temperature rotor architecture, and by using high speed Silicon Carbide transistors, the ISG and ISGC have demonstrated the ability to produce 160kW of electrical power while maximizing available space claim and minimizing their cooling burden.

4.4 **Advanced Thermal Management System (ATMS)**

The Advanced Thermal Management System (ATMS) was developed to provide a cooling system solution that reduces the amount of fan power consumption required to provide necessary cooling for the vehicle propulsion systems. This allows for more available horsepower at the sprocket, providing greater mobility in terms of top speed, acceleration, climbing capability, and range. In order to increase overall thermal effectiveness and power efficiency, the thermal management system incorporated direct cooling (all the working fluids are directly rejecting heat to the cooling air) and an infinitely variable-speed electrical cooling fan. Figure 9 shows the ATMS assembly.

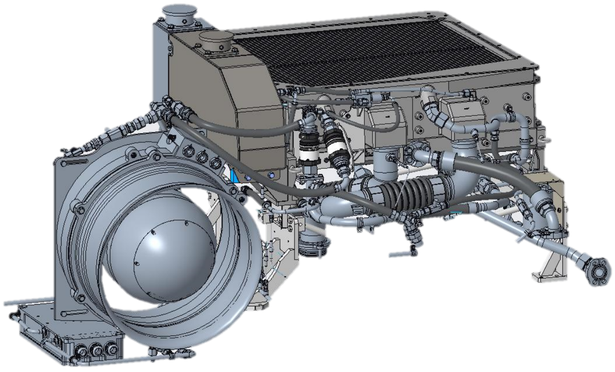

Figure 9. The integrated ATMS

The first focus area was developing a state-of-the-art brazed aluminum heat exchanger pack, taking advantage of the latest advancements in plate/fin technology. Optimization of the heat exchanger pack was guided extensively by Computational Fluid Dynamics (CFD) analysis, as well as subsystem modeling and simulation at operational and environmental stressing scenarios. The heat exchanger pack has three separate heat exchangers and three separate cooling circuits. The first layer of the heat exchanger pack is the Power Electronics Cooling System (PECS) which provides cooling to the ISG, ISGC, fan motor, and fan motor controller. The second layer of the heat exchanger pack is the engine cooling circuit which provides cooling to the ACE. The third layer of the heat exchanger is the transmission cooling circuit which provides cooling to the ACT. Figure 10 shows the heat exchanger pack. The PECS cooling circuit includes a low voltage pump, a coolant filter, and a coolant reservoir. The engine cooling circuit utilizes the engine coolant pump and integrates a coolant reservoir. The transmission cooling circuit utilizes the transmission oil pump and filters.

Cooling air is drawn through the PECS heat exchanger, then to the engine heat exchanger, and finally to the transmission heat exchanger. This particular ordering of the crossflow-type heat exchangers maximizes the initial temperature difference (between the hot- and cold-sides) of each individual heat exchanger, thereby maximizing the rate of heat being rejected to the air. Maximizing the heat being rejected into the air decreases the air mass flow rate required by the system, which results in less power to the fan.

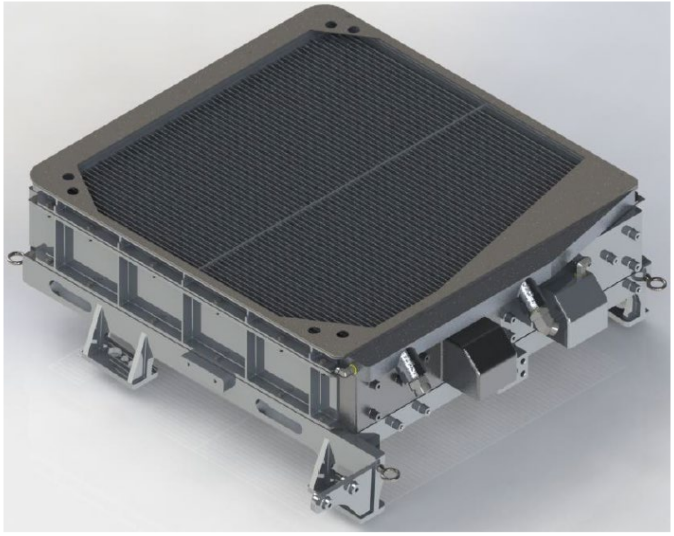

Figure 10. The heat exchanger pack

The second focus area was the development of a high-voltage fan that can meet the aerodynamic requirements of the system (air flow rate and pressure drop). In order to meet schedule and cost targets, a high-efficiency cooling fan that had been developed for another program was selected for use on the APD project. This cooling fan had originally been designed to accommodate a hydraulic motor drive. For this application, the hydraulic motor was removed and the fan housing was modified to facilitate a high-voltage, liquid-cooled electric motor. For this application, the fan motor was actuated using a remote 600 Vdc, variable-speed COTS motor drive, however the motor drive is planned to be integrated into subsequent cooling fan assemblies for future programs. Figure 11 shows the high-voltage electrical fan.

Figure 11. The high-voltage electrical fan

4.5 **Advanced Modular Batteries (AMB)**

The Advanced Modular Batteries (AMBs) are low-voltage high-energy Li-Ion batteries with a space savings over lead acid batteries of 2:1 and a weight savings of 4:1 for the same amount of energy. Packaging the batteries required vehicle design consideration as the AMBs are lighter, do not require routine maintenance and are able to be packaged in several orientations. For these reasons, typical vehicle packaging of batteries did not apply and new locations were opened up for storage. Consideration of accessibility, cable routing, airflow, and protection became the new design criteria. Because the Li-Ion batteries are smaller with more storage capability, increased silent watch time is available before it is necessary to restart the engine to charge the batteries, and because the charge time required to completely charge the batteries is considerable less than lead acid batteries, the vehicle is able to return to silent watch sooner.

4.6 **Powertrain Controls**

Powerpack control systems face the same dilemma as powerpack hardware, with COTS solutions and military requirements having diverged over the last 35 years. In many cases, COTS components are operating in vastly different environments than military equipment, which drives different software requirements. COTS engines are controlled and calibrated according to emissions regulations, robbing the engine of potential power, while military ground vehicles are exempt from emission regulations. Diesel engines are also typically fitted with additional emissions equipment, reducing the space claim efficiency. United States-based COTS engines are calibrated for a certain quality of diesel fuel readily available within the continental United States, while fuels of varying quality and cetane levels are utilized throughout the military based on location and supply chain availability, which with no software or calibration changes also reduces engine power. Military specific controls should be developed in order to work around these issues and extract as much available power as possible. However, paying for software modifications through the engine supplier has proven to be cost prohibitive. This led to in-house software controls development within GVSC, following the process outlined in [6].

In addition to control systems, the controllers themselves also have many different requirements between typical automotive and military environments. Again, trying to modify a COTS controller or having an Original Equipment Manufacturer (OEM) develop a new controller for that specific application has proven to be cost prohibitive. The neXtECU is being developed by GVSC’s Real Time Control Systems (RTCS) Team to meet these elevated requirements, also outlined in [6]. Another benefit of the neXtECU in regards to integrating systems is that due to the number and variety of inputs and outputs, it truly is a common controller, allowing it to be a capable solution for most applications, even allowing multiple hardware components to be controlled through this one singular controller, reducing logistical and maintenance burden. A common controller can also benefit from economies of scale as the controller is mass produced and used in a wide variety of applications, instead of specialized controllers being used in one application and in very limited numbers. It also eliminates complexity and weight by reducing the number of wiring harnesses from decreasing the number of on-board controllers by consolidating their features and functions into one neXtECU controller, freeing up extra space for other components on the vehicle.

The Ground Vehicle Power and Mobility (GVPM) RTCS team at GVSC led the software control effort from the APD integration level as well as developing the software to control a number of the individual components. RTCS collaborated with Cummins on the engine control software, utilizing the open tool-chain of the neXtECU, with support for both RTCS's hand-coded C-based software and Cummins' model-based software. The ATMS software was developed internal to the Government, comprising a fan control algorithm which monitors multiple cooling circuits and prioritizes fan speed based on each circuit's temperature, while maintaining an appropriate fan speed to optimize power usage, as well as coolant pump controls. To take advantage of the ISG's capability to be both a motor/starter and generator, ISG supervisory controls were developed to control the ISG operating mode, as well as controlling the bidirectional converters to either supply low-voltage power to the batteries and powerpack components, or to draw power from the batteries during an engine start. To bring all these areas together, powerpack supervisory controls were also developed internally, to integrate everything into one complete powerpack system. The supervisory controls look at multiple vehicle variables and driver inputs to determine vehicle operational modes which enable additional performance features, communicates driver inputs to the powerpack components, monitors diagnostics, and automates engine start. Along with software, the effort also included designing, building, and integrating many of the wiring harnesses, encompassing low voltage power, ground, signal, and communication. Having the same team that developed the software controls also lead the software and electrical integration allowed for rapid development and growth when faced with new requirements or changing objectives. Whether this required a quick change to a software function, or software/electrical interface, the change could happen quickly and on-site. The software features and electrical integration will continue to be expanded and improved through tighter integration with the entire vehicle as APD transitions to vehicle testing and field trials.

4.7 **Air Induction System**

The air induction system for APD was required to flow over 50% more air than the legacy system to support the increased engine power, but was confined to the same legacy space claim. To overcome this significant design challenge, a new self-cleaning filtration system was developed with Donaldson, Inc., which not only met the higher engine flow requirements within the legacy space claim, but dramatically extended filter life performance in the heavy dust conditions required for military tracked vehicle applications. The new system also requires filter maintenance checks only at scheduled annual vehicle service intervals. An added benefit of the reduction in filter maintenance is a lower chance of engine damage due to dust and debris being introduced into the clean air intake when the system is apart for service. A comparison of typical passive vs. self-cleaning dust life performance is shown in Figure 12.

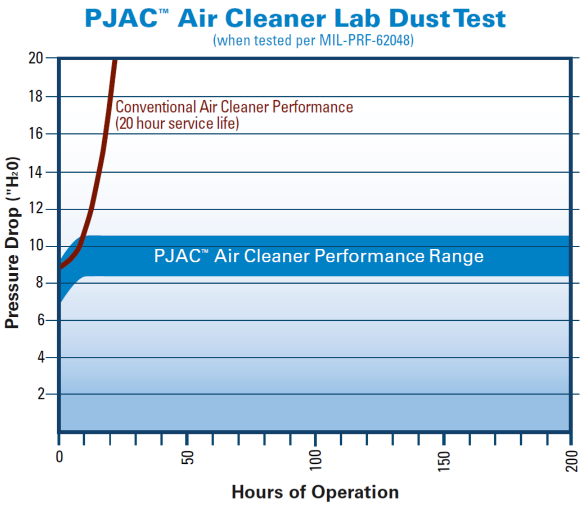

Figure 12. Typical Comparison of Conventional vs. PJAC Filter Performance (courtesy: Donaldson, Inc)

The typical legacy military filtration system, including the current Bradley system, uses a passive main filter along with a vortex-tube pre-cleaner that is scavenged using a venturi nozzle ejector in the exhaust system. The venturi nozzle uses the momentum of the exhaust flow to pull dust out of the pre-cleaner and dump it overboard before it reaches the main filter. The main filter must then be sized to hold the remaining accumulation of dust over a 20+-hour period of operation at zero-visibility dust conditions. This results in a large volume required for the main filter, and frequent filter cleaning maintenance requirements. Operationally, the passive system has a few shortcomings. The effectiveness of the exhaust venturi nozzle degrades rapidly at lower engine airflows, so when the vehicle spends extended time at part load and idle conditions typical of the mission profile, filter life is compromised. The nozzle also adds backpressure to the exhaust system. In addition, when the vehicle is operated in a convoy in dusty/sandy terrain, dust concentrations experienced by the follower vehicles can approach 20x zero-visibility conditions, overwhelming a passive system and requiring frequent stops for filter cleaning. These issues drove the original development of the Pulse Jet Self-Cleaning air filtration system by Donaldson for the Abrams tank [7].

New passive and self-cleaning systems have incorporated scavenge fans in place of exhaust ejectors to solve off-peak efficiency issues. However, some of these applications that use a mechanically-driven scavenge fan, like the Abrams, are prone to the same issue of reduced scavenge performance at low engine speeds as seen with an exhaust ejector.

For APD, a new self-cleaning Pulse Jet Air Cleaner (PJAC™) from Donaldson was designed to fit within the Bradley air filter space claim. The PJAC system actively cleans the main filter using back-pulses of high-pressure compressed air to knock dust off the filter. This dust is then drawn out of collection ducts and dumped overboard using an electric scavenge fan. This active removal of dust from the filter in a self-cleaning system allows for a much smaller filter element to be used, since the filter no longer needs to be sized for 20+ hrs of dust holding capacity.

An electric air compressor, accumulator tank, pulse valves, and controller are all packaged in the clean air stream inside the filter box. The controller monitors pressure across the filter and automatically operates the compressor and pulse valves when necessary to clean the filter. Use of an electric compressor and scavenge fan means that full self-cleaning performance is available at any engine speed. Locating the air compressor and controller in the cool intake air stream provides built-in cooling of those components within the hot engine compartment.

The APD system also uses a louvered pre-cleaner attached to the main filter element, instead of the traditional vortex-tube pre-cleaner. The two types are shown in Figure 13 and Figure 14. With the louvered pre-cleaner, air entering the filter is forced to make a sharp turn around the attached louvers, which separates the heavy dust particles entrained in the air. The separated dust proceeds to the floor where it is removed from the system by the scavenge fan. This functionality is shown in Figure 15. The louvers have a lower dust separation efficiency than a vortex-tube pre-cleaner, but that is accommodated in a self-cleaning system through a slight increase in automatic filter cleaning frequency. Importantly, the louvered pre-cleaner introduces four key advantages: first, it doesn't take up any extra space and eliminates the bulky vortex-tube pre-cleaner, leaving more room for the filter and other system components; second, it has a lower pressure drop; third, the louvers actually improve the cleaning performance of the pulse jet system by directing the dust from a back-pulse down toward the scavenge collection ducts; and finally, it eliminates the need for dedicated pre-cleaner scavenge flow, allowing for the use of a much smaller fan than similarly-sized filtration systems. As a direct result of the louvered pre-cleaner, APD at 1000 hp is able to use the same scavenge fan that is currently being used on the intake system of the 450 hp Stryker 8x8 vehicle.

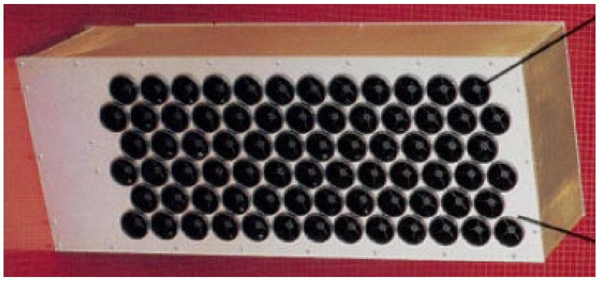

Figure 13. Example Vortex Tube Pre-cleaner (courtesy: Donaldson, Inc.)

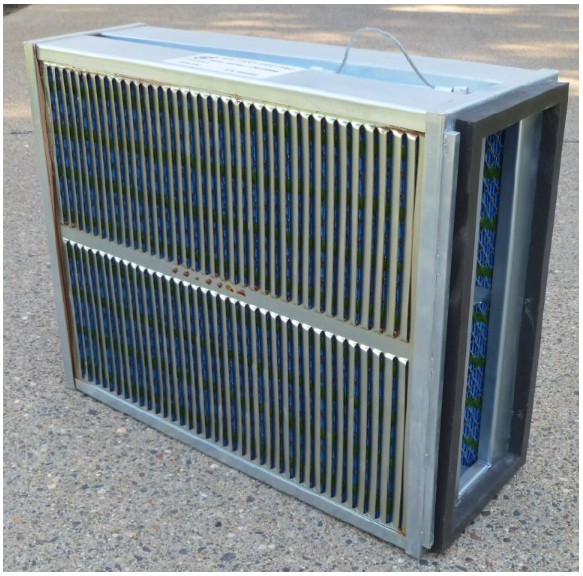

Figure 14. Vee-Pac Main Filter with integral Louvered Pre-cleaner (courtesy: Donaldson, Inc.)

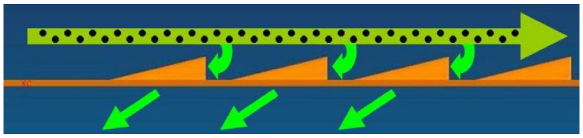

Figure 15. Illustration of Louvered Pre-cleaner Functionality (courtesy: Donaldson, Inc.)

The APD air filtration system was designed for continuous operation at up to 20x zero-visibility dust conditions, far surpassing the performance of the existing passive system, and pushes the envelope of self-cleaning system packaging density vs. airflow.

4.8 **Exhaust System**

Like the intake system, the engine exhaust system for APD was designed to flow significantly more air, stay within engine backpressure limits, but fit within the same space claim as the legacy Bradley exhaust system. To accomplish this, GVSC worked with Great Lakes Sound & Vibration, Inc. to design a new engine exhaust system for APD. This included a custom-designed muffler with acoustic attenuation tuned to the new APD engine firing frequencies. The muffler is mounted behind the cooling fan in the same space as the legacy muffler, and it uses the same outlet hood through the exit grille. As another example of the integrated nature of the APD design, the shape of the muffler was carefully optimized, through a series of iterative exhaust and cooling flow analyses, to meet the exhaust backpressure requirements while also lowering the cooling fan exit pressure loss. The exhaust pipes connecting the engine to the muffler employ ceramic coating surrounded by high-performance Pyrogel® insulation to minimize thermal load to the engine compartment. The insulation is covered with a permanent hard-coat encapsulation for improved durability. The pipes also use Linkeo® ultra-flexible insulated couplers to accommodate tolerance stack-up, thermal growth, and the relative dynamic motion of the engine. A cross-section of the Linkeo® coupler is shown in Figure 16, and an illustration of the coupler's flexibility is shown in Figure 17. The extreme flexibility of the Linkeo® coupler reduces transmitted engine vibrations through the exhaust system, and makes connecting and disconnecting the exhaust system for powerpack removal/installation significantly easier.

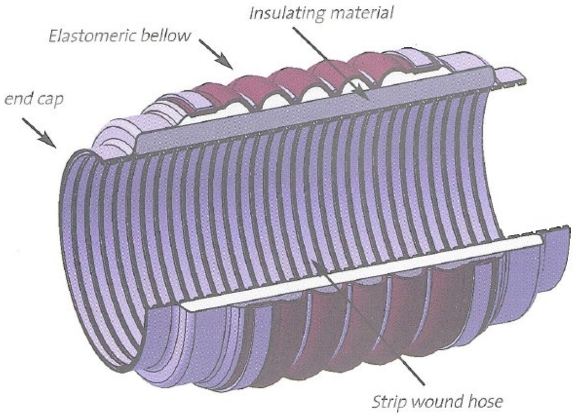

Figure 16. Linkeo® Flexible Coupler cross-section (courtesy: Hutchinson, Inc.)

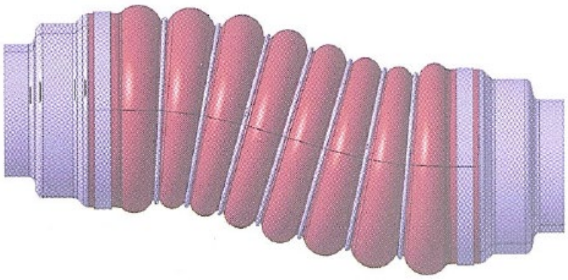

Figure 17. Illustration of Linkeo® Coupler flexibility (courtesy: Hutchinson, Inc.)

4.9 **Powertrain Integration**

Each of the component technologies discussed above, taken individually, would have a positive impact on vehicle design. In bringing them all together at once in a new powerpack design, the individual benefits build upon each other and compound, resulting in an integrated system with ground-breaking power density and performance. The tight integration required to achieve this power density was accomplished through parallel development of each component at the various suppliers, with the overall integration approach, system architecture, cooling system design, space claims, and interfaces managed internally at GVSC. This coherent integration approach enabled the entire team to maximize use of available space, even outside of rigid component space claim volumes, for a better and more-compact overall system.

Computational analysis tools were used extensively to drive the design of the APD powerpack. Finite Element Analysis (FEA) was used to verify the system for powertrain bending, and to ensure the safety and robustness of new component designs, mounting brackets, lifting hardware, and hull interfaces. CFD analysis was used to optimize the cooling system, air filtration system, and the exhaust system. Thermal analysis tools were used in the layout and design of the cooling system.

There was also a holistic effort, with input from the user community, to design the system for ease of maintainability and to minimize hull modifications required for vehicle retrofit. The hull modifications required to incorporate the APD system into the Bradley were designed to be accomplished with fixtures and basic equipment in a field environment, without the need to perform any hull machining operations or send vehicles back to the depot. Maintenance and disconnect points were located for accessibility through existing vehicle access openings. In addition, powerpack installation/removal times are improved through two key changes. First, the use of an electric cooling fan replaces mechanical PTO disconnect tasks with a single electrical connector. Second, the new transmission uses a retracting-spline final drive disconnect that eliminates the need to remove the intermediate drive shafts as required in the current vehicle.

Despite the fact that the APD solution was designed to fit within the Bradley engine compartment, the system is applicable for retrofit on other vehicles, and for use on new vehicle developments. Bradley was chosen as a demonstrator vehicle for this technology because it represented a worst-case integration challenge for a new 1000 hp powerpack. Like any powerpack, integration into a different vehicle will make use of the core components, but require adaptation of auxiliary systems (cooling, air intake, exhaust, etc.) to a new vehicle layout. For front-drive vehicles with a driver's tunnel next to the powerpack, like the Bradley, adaptation changes of the APD T-Drive configuration will be fairly minor. For rear-drive vehicles or for front-drive vehicles with side-by-side crew, a U-Drive configuration could be advantageous, and can significantly reduce the length of the engine compartment. In a U-Drive configuration, the engine is mounted transversely in the vehicle, and is connected to the transmission through a transfer gear case added onto the transmission. In this scenario, the engine could either be positioned horizontally, like in APD, to minimize engine compartment height, or vertically, to further minimize engine compartment length. The ACT can easily be re-configured with a transfer gear case for either option. The ACE block was also designed from the start to support either a horizontal or vertical orientation, and supporting engine systems can be adapted to a vertical configuration.

With a 1000 hp rating, the ability to achieve that power at elevated temperatures, and improved powertrain efficiency resulting in significantly more of that power available at the sprockets, the APD powerpack can provide high mobility performance in vehicles up to 60 tons. The technology is also scalable, with significant commonality, up to 1500 hp (future development 6-cylinder engine and ACT1500 transmission), or down to 750 hp (future development 3-cylinder engine and existing ACT850 transmission) for application in other vehicle weight classes.

5.0 APD Testing

There are two primary objectives of the APD testing. First and foremost, the testing is intended to demonstrate that the powerpack has achieved a TRL 6 maturation. TRL 6 is defined as a system or subsystem model or prototype demonstration in a relevant environment. Secondly, the testing is intended to fully characterize the APD performance across the operating envelope and to verify that the APD meets all of its requirements.

The TRL 6 maturation will be demonstrated by successfully completing 75 hours of driving on Aberdeen Proving Ground road course simulated in the GVSC/GVPM dynamometer laboratory. The simulated road course will include rolling resistance, air drag, grade, steering, and braking loads. The road courses were selected to best represent the BFV Operational Mission Summary / Mission Profile (OMS/MP). The number of laps to be conducted for each course and the average vehicle speed for each course was selected to match the OMS/MP distances and durations. Since the APD will be tested against representative Aberdeen courses, results can be compared against currently fielded vehicles in this weight class (Bradley, Armored Multi-Purpose Vehicle [AMPV], and Paladin Integrated Management [PIM]) and their near-term upgrades.

The dynamometer test cell chosen for this test has just recently finished a modernization effort. The test cell includes two, brand-new, state-of-the-art Alternating Current (AC) dynamometers capable of motoring and absorbing torques up to 285,000 ft-lbf per side at speeds as low as 5 rpm. These dynos are also capable of simulating vehicle inertias well in excess of 80 tons during both acceleration and braking. These dynamometers, being completely independent between the right and left sides, and being completely digitally controlled using state-of-the-art Horiba systems, are capable of simulating vehicle steering loads. This is a significant advancement for the US Army, being the first time that a full vehicle powerpack will be tested in steering modes in a US Army dynamometer laboratory. The GVSC/GVPM team developed the steering algorithm in-house using theoretical data and equations developed by Allison Transmission under Contract No. DA-AE07-68-C-1225 and published in [8]. The steering algorithms have already been tested on an Abrams M1A2 Main Battle Tank (MBT) in this test cell.

The APD performance testing will begin with verification of all of the APD's controls interfaces and operational features. A portion of this testing actually begins during ground hop, where a significant portion of the instrumentation is checked and all critical powerpack systems are checked for operation and leaks. The powerpack will then be installed into the vehicle chassis in the test cell. At this point a second run, similar to the ground hop, will be performed to verify the remaining instrumentation and to verify communications between the dynamometer controllers and the powerpack. This will be followed by powerpack performance envelope characterization. This characterization will include full-throttle power sweeps, full-throttle accelerations, pivot performance, steering performance, and some initial braking runs. The purpose of this testing is to understand the full envelope of powerpack performance to aid in setting up dynamometer control parameters. This will be followed by the 75 hr TRL6 demonstration test per the BFV OMS/MP. After the TRL6 testing is complete, then more thorough performance testing will be performed. This will include fuel economy mapping in all gears and at numerous engine speed and throttle settings, speed on grade, full-load tractive-effort cooling, consecutive braking, and peak tractive effort testing.

The test data will then be analyzed and compiled into a report. The findings will be used to make any final tweaks or adjustments to the powerpack integration and controls as the powerpack transitions to vehicle testing and field trials.

6.0 Follow-on Activities

The APD demonstrates the capabilities of these integrated technologies in the hull and will characterize the system capabilities in a powertrain test cell. A follow-on project, the Advanced Mobility Experimental Prototype (AMEP), has been approved which will move this capability from the test cell to field trials. That project will include integration to the vehicle's driver controls, further development of the cooling fan, integration of the power conversion electronics, integration of the batteries, hull structure studies, and Automated Fire Extinguishing System (AFES) integration as well as experimentation and data collection at a government test site.

Additionally, since the APD effort focused on integration into a vehicle and not simply the demonstration of a new powerpack, there is a detailed understanding of what is necessary to successfully integrate the powerpack into other vehicles in a similar class.

7.0 Conclusion

Using military-specific design strategies, the APD was built from the ground up to optimize a powertrain solution designed for harsh military environments, for use in both vehicle retrofits and new vehicle designs. The APD design is capable of not only adapting to legacy systems, but also of being integrated into emerging vehicles. In addition, the design focused on the impacts to the vehicle so as to minimize the changes required to any vehicles that could benefit from a powerpack upgrade. The APD Integration was a collaboration between powerpack experts, vehicle experts, and users to ensure the solution not only met the need of more power but also the requirement to be maintainable, supportable, and durable with growth capability.

8.0 References

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