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A SYSTEMS ENGINEERING APPROACH TO COMPACT AUXILIARY POWER UNITS FOR MILITARY APPLICATIONS

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ABSTRACT

AVL is developing a family of modular Auxiliary Power Units (APUs) based on the current gasoline range extender engine/generator developed by AVL for plug-in hybrid electric vehicles. These military specific variants will utilize the same basic architecture as the gasoline version while incorporating semi-direct fuel injection that is compatible with diesel fuel as well as kerosene based fuels such as F-44, JP-5, JP-8, Jet-A, etc.

A systems engineering approach to the engine, generator, and power electronics modules enables a wide range of power outputs and packaging options to be easily developed from the base unit.

INTRODUCTION

The demand for additional electrical power in military vehicles has been well documented. Advanced survivability, weapons, and Command, Control, Communications, Computers, Intelligence, Surveillance, Reconnaissance (C4ISR) equipment are driving vehicle power demands dramatically higher. Traditional vehicle power and energy architectures are inadequate to support these loads [1].

Mission profiles requiring extended silent watch operation (main engine off) for the current fleet are putting unprecedented demands on vehicle electrical systems, and future electrical power requirements for advanced platforms such as GCV continue to rise. Electrical power estimates for future HBCT and GCV platforms range from 27 kW to over 50 kW. HMMWV requirements have grown six-fold from ~2 kW in 1985 to ~12 kW in 2007.

Figure 1 shows the estimated electrical power growth for several military platforms. [1]

Two options exist for powering military vehicles during silent watch: a battery storage system and an auxiliary power unit (APU). Batteries have the advantage of little or no thermal signature and no noise emissions. However, they are heavy and require considerable volume per kW-hr of energy storage. In addition, a battery storage system capacity is based on the battery pack state of charge (SOC), the useful life of the batteries, and the ambient temperature.

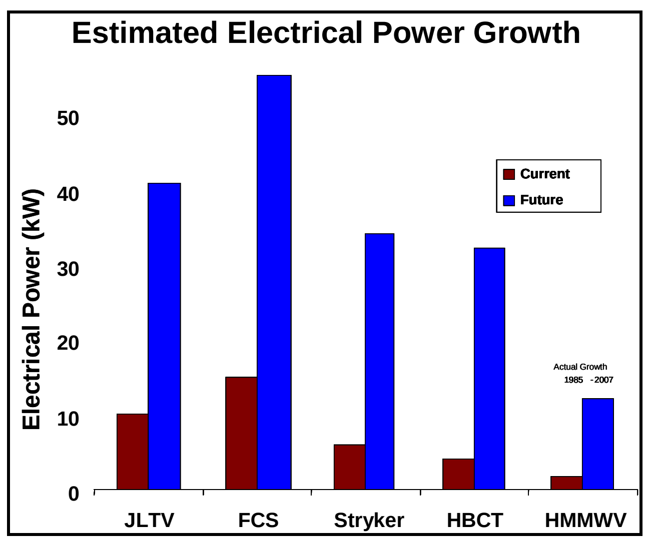


Figure 1

An APU has the advantage of high energy density (when using fuel from the main engine) but has finite noise and thermal signatures. Proper system design can minimize these characteristics.

An analysis of battery pack capacity and cost vs. run time in silent watch mode for various levels of power demand is shown in figure 2. Additionally, battery pack volume vs. APU volume is also shown. This figure assumes a $300/kWh future cost for volume produced battery packs, which is an aggressive target. It is evident that the longer the silent watch duration, the greater the advantage for the APU.

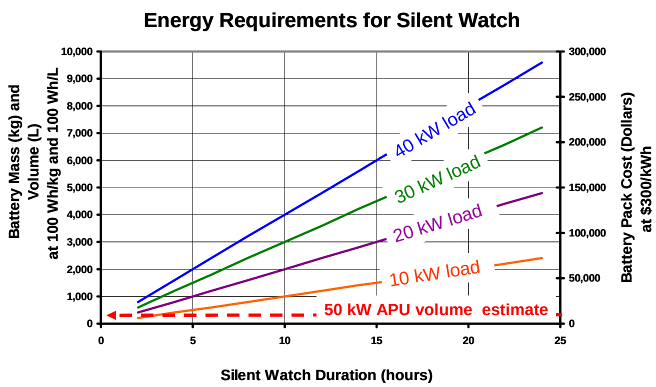


Figure 2

An additional advantage of the APU over a battery pack is the cold ambient performance. A battery pack will lose capacity in a cold environment. The pack, if also required to start the main engine, must maintain a larger amp-hour reserve in cold weather to provide the increased cranking power necessary when the main engine is cold. The available output of an APU actually increases in a cold ambient due to the decreased energy required for cooling. Further benefit can be realized if the waste heat from the APU is used to pre-heat the main powerpack. Such a pre-heat would result in a quicker start, shorter time to full power, and greater efficiency of the main powerpack immediately after cold start.

DEVELOPMENT OF THE AVL RANGE EXTENDER

The AVL solution for a compact military APU is an evolution of the AVL range extender concept for a battery electric passenger vehicle. In a pure electric vehicle, the maximum range is determined by the capacity and SOC of the battery pack. To provide sufficient range meeting customer expectations, the battery pack would be large, heavy, and expensive. ,In the AVL 1475 kg vehicle, the battery pack capacity required for a 200 km driving range (assuming 20 kWh/100 km) would be ~40 kWh [2]. A lithium ion (Li-ion) battery pack of this capacity would cost an estimated $12,000.00, weigh approximately 400 kg, and occupy 0.4 meters^3 of vehicle volume. The AVL solution was to reduce the battery pack to 10 kWh, and to include an internal combustion engine (ICE) based range extender. The 10 kWh battery pack resulted in a battery-electric range of ~50 km, which would cover 70-80% of typical daily driving distances [3]. The range extender, which is capable of 15 kW of electrical power, allows extension of the vehicle range without depleting the battery pack. Similar to a series hybrid, the range extender provides electrical power to propel the vehicle and simultaneously recharge the battery pack. The 15kW output of the range extender is adequate to power the vehicle continuously at 100 kph up a 2% grade, and enables driving well beyond the battery electric range.

THE EVOLUTION OF THE RANGE EXTENDER

Rotary Piston Engine

Out of several combustion engine concepts evaluated for the range extender, five were selected for detailed evaluation as shown in figure 3.

	Otto 2-cycle 1-cylinder piston controlled balancer shaft	Otto 2-cycle 2 cylinder opposed pistons piston controlled	Rotary Engine single piston	Otto 4-cycle 2-cylinder inline Balancer shaft	Diesel 4-cycle 2-cylinder inline balancer shaft
I NVH	0	+	++	0	-
II Package	-	-	++	0	0
III Weight	0	0	++	0	-
IV Product Cost	0	0	-	0	-
V Efficiency	-	-	-	0	++

Passenger Car Range Extender Concept Studies

Figure 3

Of the five concepts, two were selected for further development, as shown in figure 4. [4] Based on the significant advantages in NVH, packaging volume and shape, and weight, the single disc rotary piston engine was selected for the Range Extender.

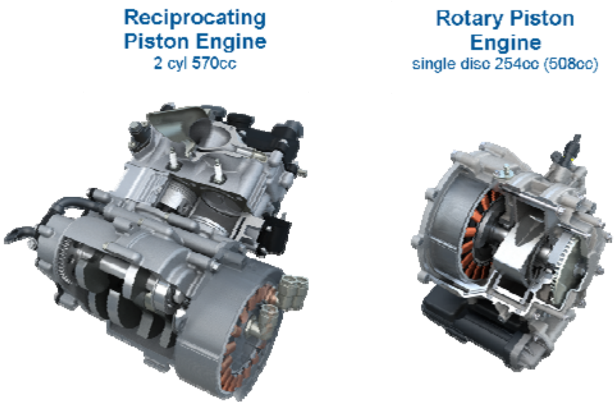


Figure 4

Due to the symmetric design, the rotary piston engine (RPE) enables a highly integrated solution which combines ICE and generator on one shaft within a common housing.

Such a concept offers the highest level of integration of ICE and generator resulting in significant weight and packaging advantages not only compared to conventional automotive ICE engines, but also in comparison to very specific reciprocating piston engines which were specially developed for Range Extender application.[4] The integration of the RPE and generator-starter (GS) are described in figure 5.

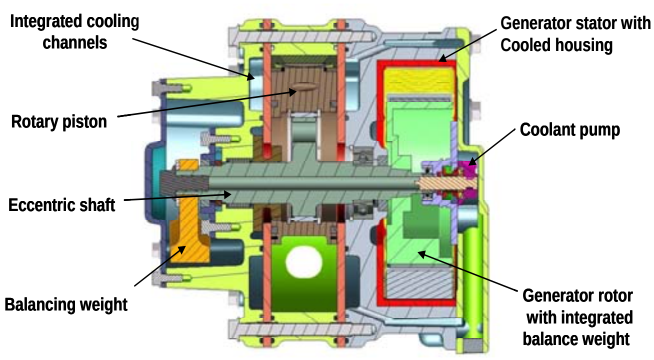


Figure 5

Because of the single speed and load operating strategy of the pure serial Range Extender, a specific application of the rotary piston engine, completely different from conventional variable speed and load approaches, is enabled. The late exhaust opening (like in an Atkinson Cycle) and the resulting extended expansion not only improves the efficiency and reduces the exhaust temperature, but also reduces the pressure pulse with exhaust opening and consequently the gas exchange noise. The optimization of all design parameters was not only based on the comprehensive experience AVL gained in the last 5 years during several rotary engine developments, but also on a model based comprehensive development approach. [4]

Generator-Starter and Power Electronics

For the generator-starter (GS) system, a similar rigorous concept analysis and decision process was employed to determine the optimum technology. A permanent magnet synchronous machine (PMSM) was selected because of its compactness, high electric efficiency and comparably low development risks. GS selection criteria are shown in figure 6. [3]

The power electronics module was selected based on proven architecture and the ability to provide a wide range of DC output voltages.

	PM Axial Flux Disc Armature	A-Synchronous Machine	PM Synchronous Machine	Switched Reluctance Machine
I NVH	0	+	+	-
II Package	+	+	++	0
III Weight	+	0	+	0
IV Product Cost	0	+	0	++
V Efficiency	++	+	++	0

Figure 6

THE RANGE EXTENDER AS A MILITARY APU

The requirements for a military vehicle APU are very similar to those of a range extender for a battery electric vehicle. Although the relative weighing of the attributes in the evaluation process may change, the dominant characteristics remain. Package volume, weight, noise and thermal signature are of major importance, while fuel efficiency and cost are still significant. However, JP-8 and DF-2 fuel compatibility are mandatory. This requirement is added to the decision matrix as shown in figure 7.

	Otto 2-cycle 1-cylinder piston controlled balancer shaft	Otto 2-cycle 2 cylinder opposed pistons piston controlled	Rotary Engine single piston	Otto 4-cycle 2-cylinder inline Balancer shaft	Diesel 4-cycle 2-cylinder inline balancer shaft
I NVH	0	+	++	0	-
II Package	-	-	++	0	0
III Weight	0	0	++	0	-
IV Product Cost	0	0	-	0	-
V Efficiency	-	-	-	0	++
VI JP-8 and DF-2 Compatibility	-	-	++	0	++

Additional Military Fuel Requirement

Figure 7

Additional features highly desirable in an APU are:

- Model based design
- Scalability
- Component and interface commonality
- Modular system architecture
- Multiple fuel capability
- Cold start characteristics
- Configurable high voltage output

Model Based Design

Design of the AVL Range Extender in the required timeframe required a high degree of utilization of AVL modeling and simulation tools. BOOST was used for 1-D thermodynamic modeling. FIRE simulation and VISEO analysis were used for 3-D port flow, mixture preparation and combustion simulation. An example 1-D BOOST model is shown in figure 8. An example of simultaneous shaft bending and CFD optimization of the cooling system is shown in figure 9. These tools allowed for rapid optimization of the combustion process, mass and energy flow, and cooling requirements for the RPE and GS.[3]

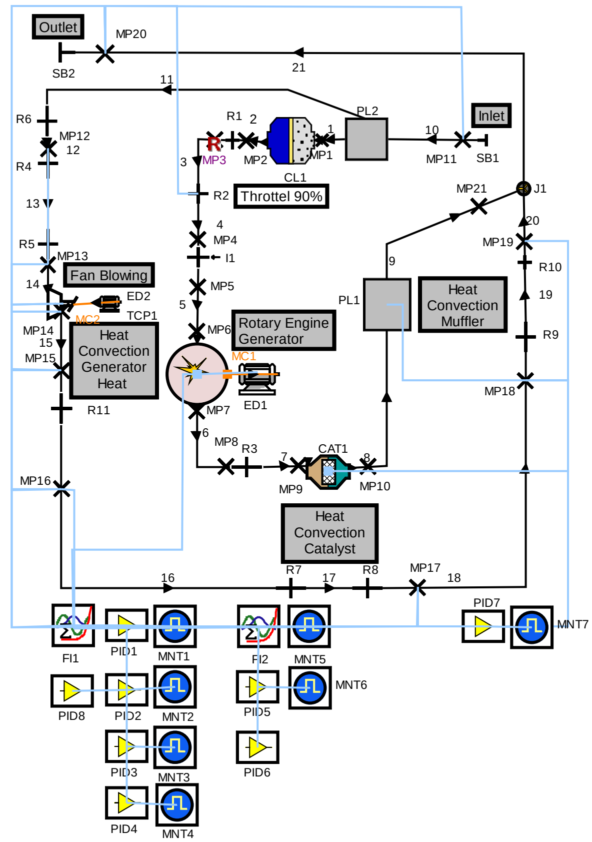


Figure 8

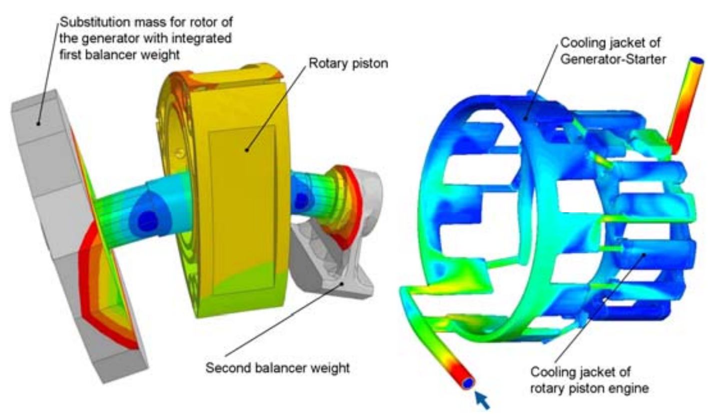


Figure 9

Similar tools and models were utilized during the design of the starter-generator and optimization of its electrical and thermal characteristics. Design layout and analysis examples are shown in figure 10

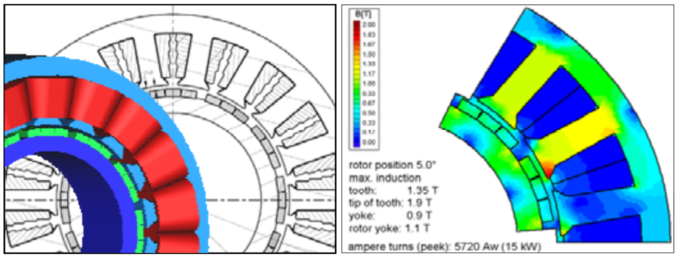


Figure 10

Scalability

The initial defined engine speed of 5000 rpm represents an optimum operating point for use as a Range Extender. The specific displacement of 254ccm represents a compromise between the boundary conditions of low fuel consumption, long engine life, low noise signature, and required potential for a further performance increase. The thermodynamic simulation in the AVL BOOST model has shown that different levels of performance in the range from 15 up to 25kW can be achieved with the same RPE hardware by increasing mean effective pressure and engine speed. By extending the rotary-piston width by 20mm, the displacement increases to 357ccm and the potential electric output increases to approximately 36kW.[3] The GS output is increased by lengthening the rotor while keeping the diameter constant. Figure 11 shows a comparison of the 15 kW, 25 kW, and 36 kW variants.

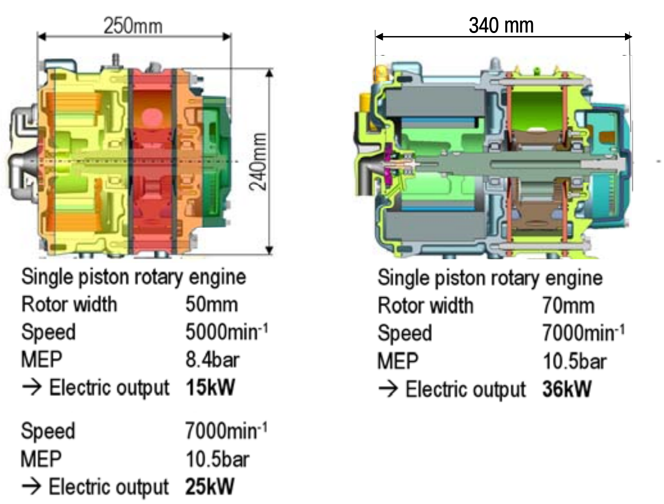


Figure 11

With the multiple uses of identical rotary piston units, higher output variants become feasible as shown in Figure 12.

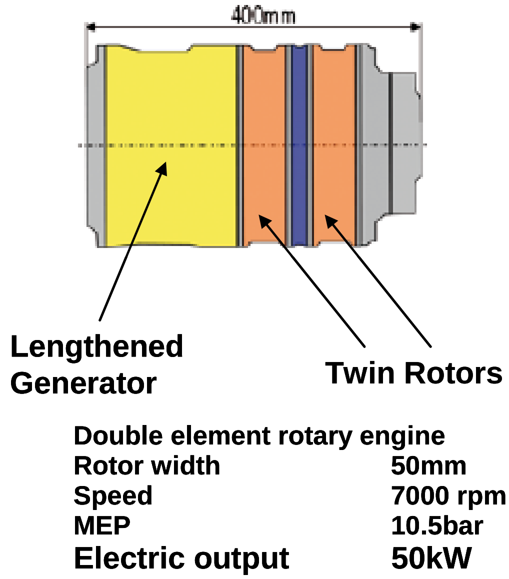


Figure 12

Component and Interface Commonality

The production orientation of the system layout is characterized by individual component design and especially by system flexibility to meet different target vehicle requirements at a high degree of common parts and production processes. The interface design of the key system functionalities and the scalability of the RPE and the GS allow a compact adaptation of the system performance for diverse applications.

The displacement and the RPE-specific parameters (base-circle radius, eccentricity and rotor width) were especially defined to allow a high number of performance variants of natural aspirated single or multiple rotor engines in the range of an electric output from 15 – 50kW while maintaining a high degree of component commonality (side part, housing, trochoid, rotors and periphery parts). Even with an increased width of the rotor, production similar bearing housings and side plates can be used due to identical key machining dimensions. The manufacturing of components like the trochoid housing and rotors is intended on common machining centers to maximize production equipment utilization as shown in Figure 13 [3].

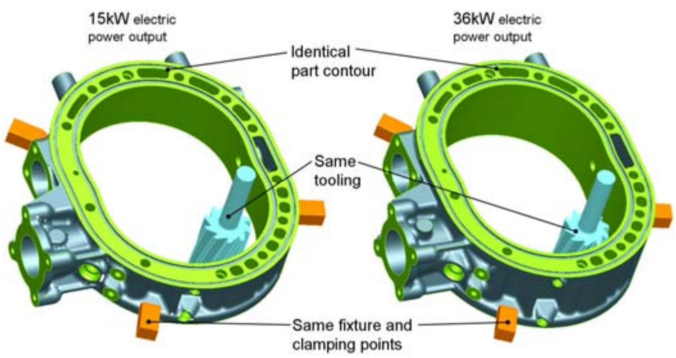


Figure 13

Modular Architecture

The modular design philosophy utilized in the APU is continued in the incorporation of ancillary components to comprise an APU system. The "core" of the APU (RPE, GS, housings) remains consistent while several independent modules are incorporated to produce system variants. These independent modules include:

- Intake system and air filter
- Exhaust system and silencer
- Lube pump and oil pan
- Power electronics module
- Heat Exchangers

The model based system architecture allows these ancillary components to be selected or designed based on individual system performance and packaging requirements. Selected components may, depending on the application, be located within the APU space claim or external to the APU.

An example of the modular build-up of the range extender version is shown in Figure 14.

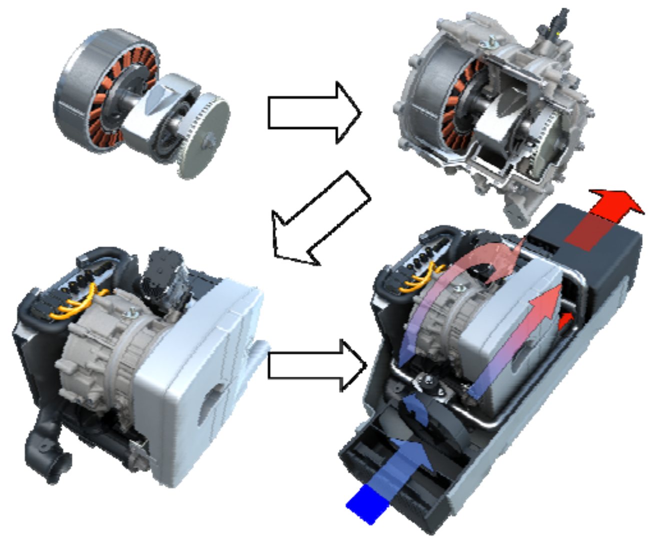


Figure 14

The minimum dimension of the core module remains at 240mm for all variants from 15 kW to 50 kW. Since the core module can be oriented in any attitude that the application requires, a large number of applications can be configured from the same core module. Application-specific ancillary components can be arranged based on remaining package shape and volume.

Packaging examples from Abrams and Bradley are shown in figure 15.

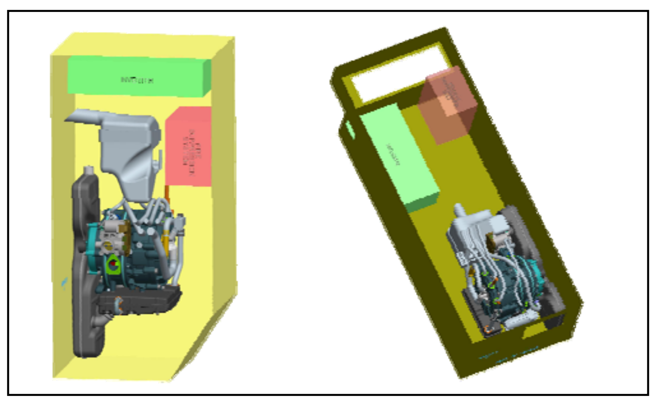
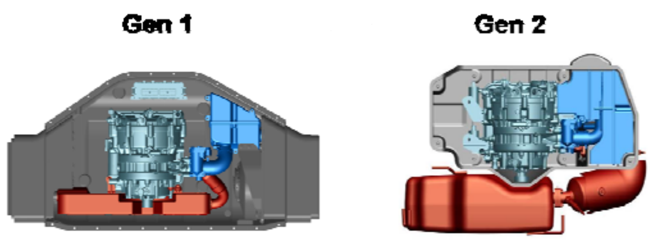


Figure 15

An example of two distinct APU packaging philosophies is demonstrated in the evolution of the AVL Range Extender system from a self-enclosed module to one with an external exhaust system.

In Gen 1 of the AVL passenger car Range Extender, the module concept dictated a self-enclosed structure: the intake and exhaust systems were arranged within the enclosure. Due to packaging restrictions, the volumes and shapes of the intake and exhaust silencers were compromised. In Gen 2, the modules were re-designed to allow the exhaust system to reside outside of the enclosure. This resulted not only in the desired reduction in NVH, but also a decrease in system mass and volume were realized, as shown in figure 16.[4]



	Gen 1	Gen 2
Volume Intake System - l	4,3	7,8
Volume Exhaust System - l	8,9	18,2
Volume Box - l	102	88
Power for box cooling - W	100 W → >200W	no add. cooling

Figure 16

Although this packaging example is based on experience with the AVL EVARE range extended passenger car, the same concept holds true for solving packaging challenges in military vehicles.

Multiple Fuel Capability

For at least two decades the concept of "Single Fuel Forward" utilizing JP-8 has been prevalent in military logistic strategy for the U.S Armed Forces. Reality dictates that military operations still need to be able to function on whatever fuel (kerosene based or diesel) is available in the theater. A relative insensitivity to fuel properties and fuel type is a desirable characteristic for a military APU.

The combustion and fuel delivery system of the AVL APU is capable of operating on a wide variety of fuels. The fuel mixture preparation is by semi-direct fuel injection and the combustion event is spark ignited. The majority of the fuel delivery components (~95%) can be effectively used with gasoline, kerosene based fuels such as F-44, Jet-A, JP-5, JP-8, and diesel fuels such as ultra low sulfur diesel and conventional DF-1 and DF-2. This system has been extensively field tested on both gasoline and kerosene based fuels.

A moderate compression ratio makes the APU relatively insensitive to octane rating, and the spark-ignited flame front combustion process is less sensitive to auto-ignition properties than compression ignition engines.

The combustion and fuel delivery systems used in the AVL APU have been proven to operate on both gasoline in passenger cars and on kerosene based fuels in unmanned aircraft drone applications.

Cold Start Characteristics

Several characteristics of the AVL APU contribute to ease of starting in cold ambient temperatures:

- Low friction roller bearings
- Low pressure, electrically driven oil pump
- Generator doubles as 15kW cranking motor
- Ability to crank engine at operating speed
- Spark based ignition system (not compression ignition)
- Optional fuel temperature management

Configurable High Voltage Output

Power Electronics for the AVL APU can be configured for DC output at any voltage between 200 and 820 VDC using developmental power electronics. This enables the APU output to be matched to the voltage of the largest electrical loads for best efficiency. Additional DC-DC converters can also be employed to satisfy multiple bus voltages such as legacy 28V systems. The inverter electronics are significantly oversized to ensure reliable operation at anticipated power levels.

SUMMARY

The AVL Range Extender has been shown to have many desirable characteristics as the basis for a military APU. Extensive vehicle evaluation along with hundreds of hours of dynamometer development and durability testing has proven the system robustness.

By utilizing advanced simulation and modeling tools, the Range Extender has progressed from inception to real world testing and evaluation in less than 12 months. These same models can be used to rapidly evolve the current Range Extender into a series of APU models to meet the present and projected future APU needs of military combat vehicles, logistic and transport vehicles, and any other application where compact, lightweight electrical power is required.

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