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DESIGN OVERVIEW OF THE R350C ROTARY DIESEL ENGINE SERIES

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ABSTRACT

This paper explains the major features and development results of the R350C rotary diesel engine series recently developed by Combat Propulsion Systems division of L-3 Technologies. This new rotary diesel engine series has been engineered specifically to operate on military grade fuels (JP-8/F24) and perform in power dense military applications, including auxiliary power units, hybrid propulsion and lightweight primary propulsion for combat vehicles. The rotary design allows for single, dual and triple rotor engine configurations with increasing power and power density ratings with each added rotor.

Disclaimer:

INTRODUCTION

The US Army has expressed the need for lightweight, power dense systems that operate on logistically available fuels (JP-8/F-24) for use in auxiliary power units, hybrid propulsion, and lightweight primary propulsion systems for combat vehicles.

The main driver in the usage of these systems is to reduce the logistical burden in supporting military units. This is of benefit, not only from a fiscal perspective, but from an operational security need that allows combat vehicles to travel further or operate longer between fuel replenishment stops. This offers the frontline commander greater flexibility in the deployment of his troops and reduced risk in his logistical supply lines.

Additionally, the increasing usage of highly mobile, lightweight combat vehicles has directed a spotlight on the need for a lightweight engine solution that can operate on military grade fuels. Many of the lightweight vehicles currently in use or have been proposed either have COTS gasoline powered engines or heavier, COTS reciprocating diesel engines. These choices result in vehicles with an increased logistical burden due to the non-standard fuel or compromises in vehicle performance due to the increased weight of the powertrain.

The R350C rotary diesel engine series addresses these needs through the following 5 attributes:

1. JP-8 / F-24 fuel capability
2. Lightweight (up to 0.5 hp/lb)
3. Fuel Efficient (best bsfc; 0.48 lbs/hp-hr)
4. Volumetric power density over twice that of traditional combustion engines
5. Scalable configurations from one to at least 2 or more rotors at 45 hp/rotor

These features distinguish the R350C engine from all other potential combustion engine solutions for military auxiliary, hybrid and lightweight primary power applications. The R350C rotary diesel engine is uniquely qualified to perform in such applications and its design and development will be highlighted in the following areas.

- Target applications – critical requirements and current technology state
- R350 design history and evolution
- Systems engineering methodology and development tools
- Design features, functional capabilities and application benefits
- Potential development opportunities

Target Applications

The U.S. Army has a need for high power density, small displacement engines that have the capability to operate on logistically available fuels. This is typically MIL-DTS-83133 (JP-8) or NATO F-24 fuel.

U.S. Army combat vehicles have requirements to operate onboard vehicle equipment for extended missions with the main engine turned off. This is typically described as “silent watch”, “mounted surveillance”, or “stationary watch” and is achieved using energy storage devices or engine driven Auxiliary Power Units (APUs). However, energy storage devices, such as batteries, provide insufficient energy to fully meet the duration of engine-off missions. This problem is only compounded as more advanced equipment is added to military vehicles. To address these requirements, Auxiliary Power Units must be compact and power-dense, while simultaneously being efficient and reliable. Currently fielded military APUs are typically based on naturally aspirated commercial off the shelf heavy duty diesel engines. This means very high weight, low power output, and old technology. With lower power output, vehicle APUs are not able to provide sufficient power to meet the future vehicle requirements, including increase communications, computerized systems, and even simple air conditioning.

The R350C engine targets military APU applications because of its compact size, high power output, and efficiency. An increase in APU power enables future capabilities including added communications, energy weapons systems, vehicle cooling capability, and energy-based protection systems.

The U.S. Army also has a growing need for compact military engines to act as prime movers for smaller vehicles as the Army transitions to an expeditionary force. Army doctrine "Force 2025 and Beyond" explicitly describes expeditionary missions as a key challenge in the future. The means that compact power systems are critical for the Army's success as unmanned systems, utility vehicles, and all-terrain vehicles are fielded. The R350C is designed to address these needs by shedding weight and increasing power output while not sacrificing efficiency.

R350 Design History

Beginning in 2009, L-3 CPS began the development of the R350 rotary diesel engine family. The R350 rotary diesel engine family is a Wankel style rotary engine, with high pressure, direct injection and spark assisted ignition that has been designed to operate in extreme environmental conditions and run on military and non-military heavy fuels (JP-8/F-24, JP-5, DF-2, Jet-A). The housings and rotor are liquid cooled for improved power density and full pressure lubricated journal bearings for durability. The engines are also turbocharged to increase power density and to improve engine performance at altitude and high ambient temperature conditions. The R350 family is currently available in single and twin-rotor versions (R351 and R352) with power levels of 45 hp and 90 hp, respectively. A preliminary R353 design with three rotors also exists at 135hp.

Since the start of development, the R350 rotary diesel engine design has gone through 2 design revisions. Each has incrementally improved the performance and packaging of the engine. The revised versions are denoted alphabetically, beginning with the letter A. The 1st revision of the R350, named the A-Series, was built and successfully demonstrated rotary diesel engine technology. The B-Series was an incremental design to improve the engine performance and the number of rotors allowed in the engine family. The latest revision of the R350, the C-Series, was designed from the ground up to overcome several issues encountered as a result of the improved performance in the B-Series variant and to make significant improvements in packaging for application integration. The R350 rotary diesel engine family specifications are listed in Table 1 below.

Series	R350 A-Series	R350 B-Series	R350 C-Series
Max Number of rotors	1	2	3
Power per rotor	45 hp @ 6000 rpm	45 hp @ 6000 rpm	45 hp @ 5000-6000 rpm
Best Fuel Consumption	0.60 lbs/hp-hr	0.52 lbs/hp-hr	0.48 lbs/hp-hr
Best Oil Consumption	>10 g/hp-hr	>10 g/hp-hr	< 4 g/hp-hr
Fuel System	Integrated, oil lubricated, high pressure pump (1600 bar) w/ diesel common rail and diesel injector		
Ignition System	Spark Assist		
Cooling System	Oil	Oil	50-50 WEG
Oil System	Wet Sump	Wet Sump	Dry Sump
Oil Type	15W-40 per MIL-PRF-2104		
Ambient Temperature	-25°F to +125°F		
Pitch and Roll Operation	± 30°	± 30°	± 60°
Durability Tests Completed	150 hr FAR Part 33.49 @ 32 hp	50 hr NATO AEP-5 @ 42 hp	50 hr FAR Part 33.49 @ 45 hp

Table 1: R350 Rotary Engine Family History and Specifications

Design Methodology

Contrary to the evolutionary design methodology of the A and B-Series versions of the R350 diesel rotary engine, the design of the R350 C-Series engine utilized a clean sheet, application centric, systems engineering approach. To design the R350 engine family to meet a wide variety of needs for different applications, the targeted applications were first identified and then their requirements were compiled and prioritized. The prioritization of requirements were as follows:

- Auxiliary Power Units / Hybrid Propulsion
- Unmanned Aerial Vehicles
- Lightweight Primary Propulsion Unit

This prioritization meant that the requirements for the APU's and Hybrid Propulsion systems were translated into the threshold requirements, and the UAV and primary propulsion system applications were set as objective level requirements for the C-Series design. The application requirements plus a failure mode assessment of the A and B-Series engines rounded out a complete engine level requirements set.

The critical requirements for the C-Series were as follows:

- Engine Durability
- High Underhood Temperatures
- Low Installation Height
- 45 hp @ 6000 rpm
- 0.46 lbs/hp-hr fuel consumption
- 4 g/hp-hr oil consumption
- 60° pitch and roll
- Full power transmission to axial and parallel shaft consumers

As the requirements were cascaded down to the sub-systems and components of the engine, the program schedule, cost and timeline factors were taken into account, the prioritization allowed the design team to focus on meeting the threshold requirements and either reserve space claim or performance capability for the objective requirements.

The resulting design fully meets the requirements for an APU application, while leaving space claim constraints and performance capacity for integration into a UAV or ground vehicle application.

Design Features and Capabilities

Due to the power requirements of the intended applications, the C-Series design retained the displacement dimensions (eccentric and rotor width) and combustion geometry developed on the B-Series engines. This allowed power to remain at 45 hp per rotor and known thermal and structural loads to be carried over to the C-Series engine.

Several other features were carried over from the B-Series engines. One highlight is the lightweight (217 g), single plunger, high pressure fuel pump (Figure 1), which can supply fuel at pressures up to 1600 bar and has enough capacity to support over 100 hp.

Figure 1: High Pressure Fuel Pump

A major change to the C-Series was a significant increase in structure stiffness to further improve engine durability and fuel efficiency. The structure of the engine was modified and analyzed using FEA to allow for a 20% increase in firing pressures and a 45% reduction in stress on the housings of the engine.

The increase in firing loads for the C-Series, improvements in the combustion, and packaging requirements of the engine led the team to search for improved ways to transfer heat to and from the cooling medium. Using conjugate heat transfer FEA/CFD simulation, significant changes to geometry of the cooling passages in the engine and a change to the cooling medium from engine oil to traditional 50-50 Water-Glycol (WEG) predicted a 45% reduction in peak metal temperatures (Figure 2). In addition, the utilization of WEG as the primary cooling medium, allowed the size of the cooling package to be reduced by 65% and weight to be reduced by 10% over the engine oil cooling system of the A and B-Series engines.

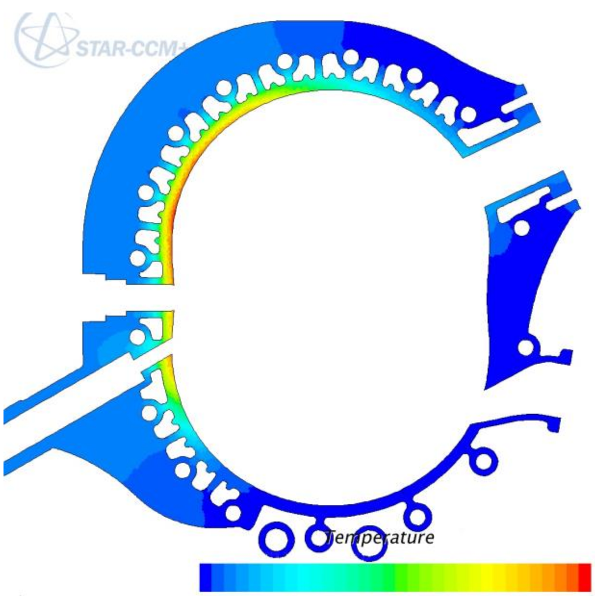

Figure 2: R350 Metal Temperature Analysis

To meet the maintenance intervals required for the various applications, the oil consumption of the engine needed to be reduced. This was achieved by replacing the traditional cast iron scrapping ring used in typical, oil cooled rotor applications with a lip seal. This design feature, along with electronic oil injection control reduced oil consumption to less than 4 g/hp-hr.

To meet the application installation height and operational attitude capabilities, the R350 C-Series was equipped with a dry-sump scavenge system. This reduced engine installation height by 3 inches, allowing it to fit in space claims as short as 13 inches.

Additional application integration improvements include bearing capacity and space claim availability to operate accessories such as electrical generation equipment and pumps. The bearings on the output of the engine were designed with excess margin to allow for full power output through a cogged belt (ex. Propeller speed reduction unit) or CVT belt transmission.

Mounting provisions for the R350 C-Series were designed and analyzed to allow for the engine to be mounted either at the bottom of the engine or by its front cover (Figure 3). Additional provisions were designed into the rear cover of the engine to accept bellhousings or other structural adaptors for items such as large permanent magnet generators or transmissions (Figure 4).

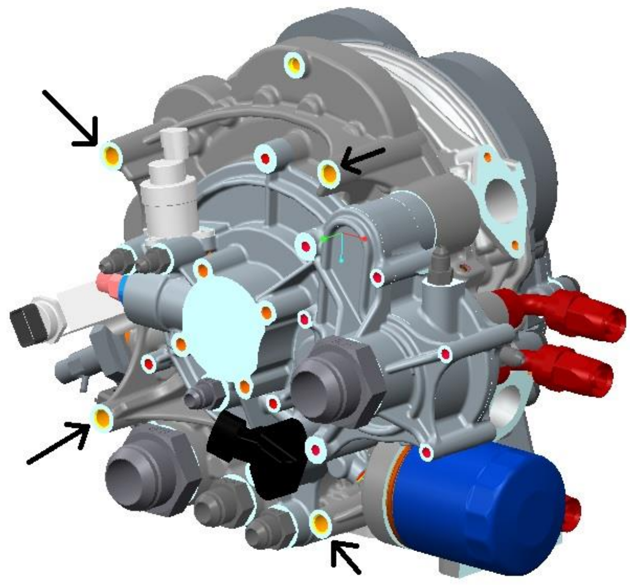

Figure 3: Front Mounting Locations

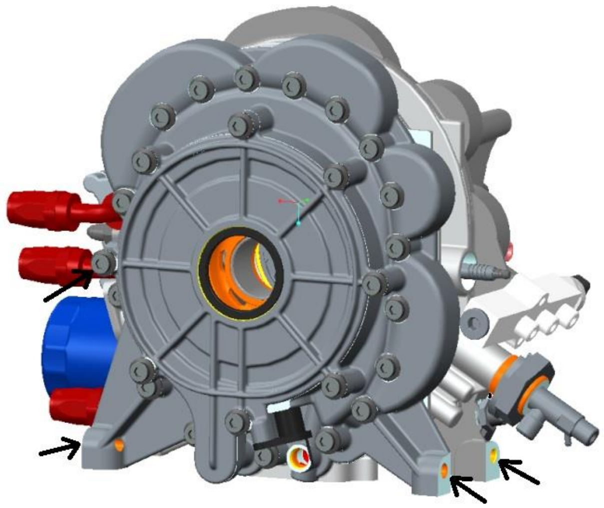

Figure 4: Rear Cover and Bottom Mounting Locations

Hardware for the R350 C-Series engines in one and two rotor versions was purchased and testing has started on the single rotor (R351) version of the engine (Figures 5 and 6).

Figure 5: First R351 C-Series Engine

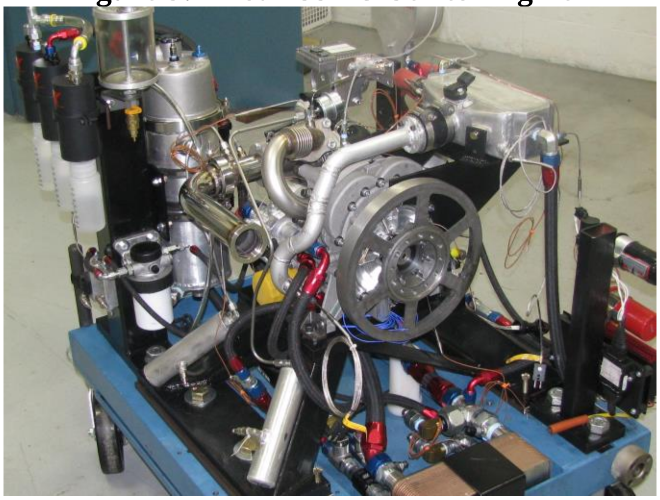

Figure 6: R351 C-Series, Dyno Test Cart, Accessories and Instrumentation

To date the two R351 C-Series engine have accumulated 250 hours of motoring and firing tests, with one engine having accumulated 150 hours of firing tests, of which 50 hours are on the FAR Part 33.49 profile operating at a peak power of 45 hp at 6000 rpm. Testing has verified the structural and cooling system improvements, oil consumption targets and dry sump oil system function. Fuel consumption has achieved a best of 0.48 lbs/hp-hr with further combustion and accessory performance identified to achieve the 0.46 lbs/hp-hr target.

Testing confirmed that improvements in sub-system integration and peak firing pressures on the C-Series engines increased peak torque to 47 ft-lbs at 5000 rpm, which provides peak power (45 hp) to be available from 5000 to 6000 rpm.

Development Opportunities

The R350 C-Series diesel engine is operational and ready for integration and prototype application level testing at its current performance level.

One opportunity that has already begun concept testing is the integration of the R351 engine and a permanent magnet generator (Figure 7). L3 created the Mobile Test System to validate the APU concept and to create a highly mobile and flexible test system to assist in environmental and controls testing.

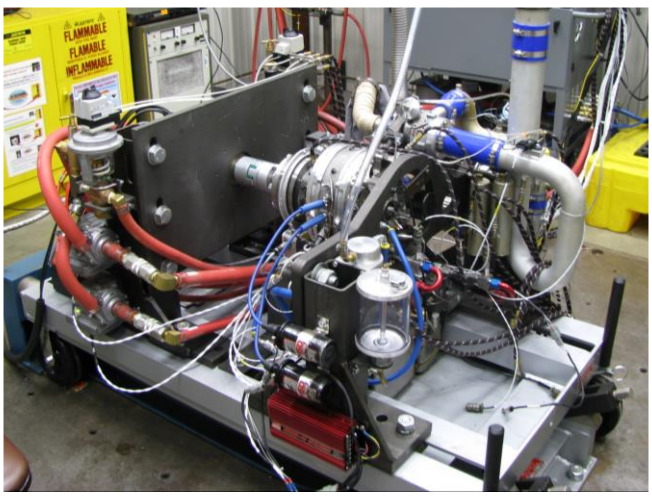

Figure 7: Mobile Test System

In addition to the current performance level of the R350 C-Series engine, L3 CPS has identified paths to higher power, improved fuel efficiency and reduced weight.

During the design phase of the C-Series, tests conducted on a larger and heavier R500 (500cc per rotor) engine proved power outputs of at least 200 hp/liter (70 hp per rotor on the R350) at 8000 rpm are possible from a direct injection, spark assisted rotary engine. Subsequently, all of the rotating components of the R350 have been analyzed to ensure capability at 8000 rpm. In addition, the improved cooling system in the C-Series has sufficient margin to allow sustained operation at those higher power levels. Preliminary testing at the required BMEP levels and operation up to 7000 rpm on the R350 has supported the calculations that 70 hp rotor is possible.

Opportunities to reduce fuel consumption by up to 15% have also been identified. Due to the large seal area and elongated combustion shape that has historically plagued the rotary engine with high parasitic friction and poor combustion, analysis and component testing have identified methods to reduce friction and improve combustion performance. Reductions in friction can be realized through optimization in seal and engine geometry as well as material selection to improve friction coefficients. Combustion performance is being enhanced by a unique injector configuration that is under an SBIR development program and has shown up to a 10% improvement in fuel efficiency under various operating conditions.

For those seeking the highest power to weight propulsion system outside of a turbine, the diesel rotary engine can deliver. The scalability of the rotary engine allows for only marginal increases in engine and accessory weight as the number of rotors is increased. This results in dramatic improvements in power to weight ratio as the number of rotors increases.

During the design of the C-Series engine, extra material and features were retained in the design to allow for maximum flexibility and number of integration features. This sets the current power density of a complete power pack (engine, oil system, cooling system, induction system) at 0.31 hp/lb for a single rotor engine. An increase in the number of rotors up to a 3 rotor version improves the power density of the power pack up to 0.5 hp/lb).

Through deletion of unneeded features and usage of alternative materials (Titanium, high temperature plastics), power density can be increased up to 0.44 hp/lb for the single rotor engine and up to 0.71 hp/lb for the triple rotor engine. If higher power levels (up to 70 hp/rotor) are factored, the power to weight ratio range of the R350 engine family increases to 0.69-1.1 hp/lb. This provides a engine family that is directly scalable from 45 to 210 hp.

Model	Displacement (cc)	Rated Power (Hp)	Engine Dimensions H x W x D (In)
R351	350	45	12.5 x 19.5 x 10.5
R352	700	90	12.5 x 19.5 x 14
R353	1050	135	12.5 x 19.5 x 17.5

Figure 8: Current R350C Power and Size

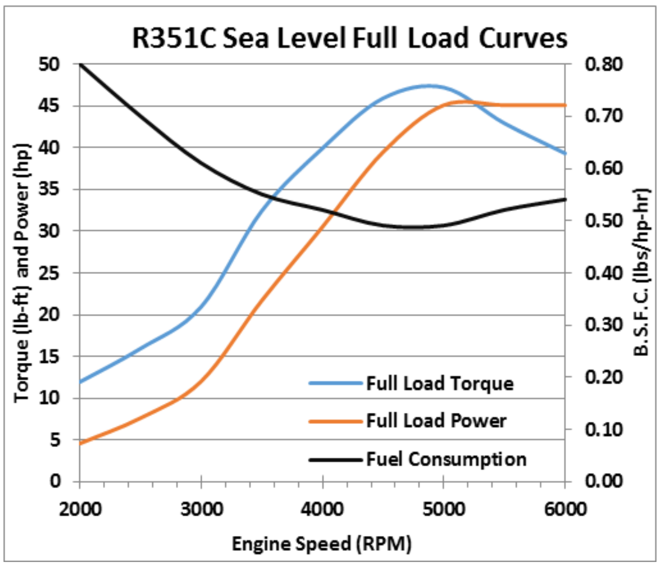

Figure 9: Current R350C Power Curve and Fuel Consumption