The Rotapower® 5-Stroke Engine Overview

Background of the Rotary Engine based on the Wankel Design

When the rotary engine was first introduced in the early 1960s, it was thought by many to be the most important mechanical invention of the 20th century. With two moving parts it seemed to be the perfect replacement for the complex piston engine with many more moving parts. The Wankel rotary engine was also much smaller and lighter than a piston engine.

Virtually every automobile and aircraft company became enraptured by its potential and during the following 30 years spent over $10 billion in today's dollars trying to get this rotary engine to match the fuel consumption of the automotive piston engine.

There are two fundamentally different Wankel type rotary engine designs depending on the method used to cool the rotor:

- Oil cooled rotors used by GMC, Mazda, NSU, Syrano, and Ingersoll-Rand
- Charge or air-cooled rotors were used by Outboard Marine Corporation (OMC), Norton Motors, Moller International (MI), Infinite Engine Company (IEC) Fichtel-Sachs, and currently by Freedom Motors (FM)

The oil cooled rotor requires complex composite side-seals to retain the oil in the rotor. Power is lost as the cooling oil is accelerated in the rotor. However, for a given displacement an oil cooled rotor rotary engine produces more power due to its higher volumetric efficiency (cooler intake charge).

The charge cooled rotor is much simpler and weighs significantly less for a given horsepower than the oil cooled rotor design and was used mostly in recreational vehicles where a long life was not required. Following its acquisition of the entire rotary engine assets of MI, GMC, OMC and IEC, Freedom Motors began a research and development program to extend the life of the charged cooled rotary engine. This program led to the issuance of three critical patents with five patents in process. Freedom Motors subsequently developed a family of charged cooled rotary engines ranging from single rotor 27cc and 150cc displacement engines to multi-rotor 530cc and 650cc displacement engines. These Rotapower® engines have been successfully demonstrated in a number of utility, recreational, and transportation applications.

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Attributes of this Rotapower® engine (4-stroke non-compound version):

- Very high power for its weight and volume
- Able to use contaminated biogas as a fuel
- Documented seal and wear surface life of over 20,000 hrs.
- Fuel consumption competitive with commercial engines

Limitations of this Rotapower® engine (4-stroke non-compound version:

- High surface to volume of the combustion chamber reduces combustion efficiency
- Compression ratio is limited to 9 to 1 to reduce combustion inefficiency
- Exhaust temperature is high due to slower combustion burn rate
- Fuel consumption is above that of the best automotive engines due to pressure and thermal energy loss in the exhaust

Compounding the Rotapower® Engine to Improve Fuel Consumption

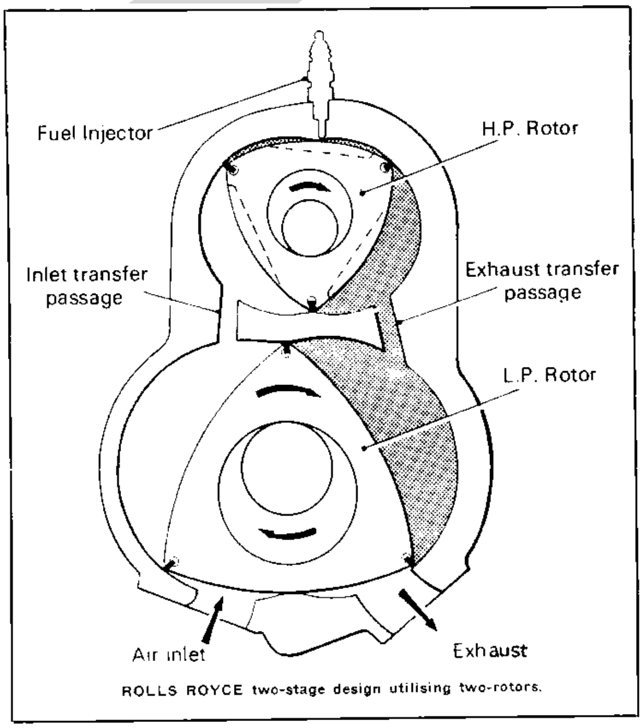

Figure 1

Compounding involves using exhaust energy to supercharge the intake charge and in addition, extract mechanical energy directly from the exhaust. Compounding the Rotapower® engine was achieved by adding a **fifth stroke** (second expansion stroke). This involved the use of two rotors in series where the first compression/expansion (CE) rotor supercharges a second power rotor. Following combustion in the power rotor, the exhaust gases reenter the CE rotor where additional energy is extracted through a fifth stroke.

In 1969, Rolls-Royce (RR) was the first company to demonstrate a compound rotary engine. In the RR design, a large compression/expansion rotor was used in conjunction with a smaller power rotor. The two rotors were connected by a chain drive and operated on separate crankshafts as shown in Figure 1. The resulting four stroke RR engine was smaller than the diesel fueled piston engine RR was hoping to replace but it would have been much heavier as an automotive engine. However, RR was forced into a Chapter 11 reorganization which prevented further development. RR did achieve a SFC of 0.375 lb./hp.hr. which was the lowest SFC recorded for a rotary engine at that time.

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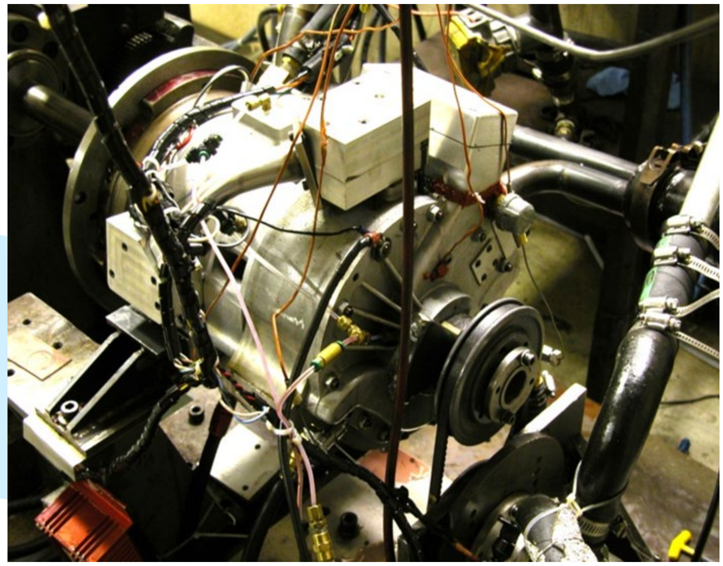
Freedom Motors has developed and dyno-tested a compound version of its charged cooled rotary engine. This compound Rotapower® engine, as shown in Figure 2, is simpler than the RR design by using charge cooled rotors operating on the same shaft. Dyno tests have demonstrated that compounding achieves the following:



Freedom Motors 530cc Compound Rotary Engine on Dynamometer

Figure 2

- **High Volumetric Efficiency.**
  Achieved through supercharging.

- **Low Noise.**
  The very extended expansion cycle reduces the exhausting gases to near atmospheric pressure eliminating 94% of the noise prior to muffling the remainder.

- **Lower Surface to Volume Ratio.**
  Supercharging allows the power rotor compression ratio to be reduced which lowers the surface to volume ratio.

- **High Effective Compression**.
  Sufficient to provide combustion ignition if used as a diesel engine.

- **Lower Exhaust Temperature.**
  Reduced from 1,600°F to less than 1,000°F.

- **Fuel consumption reduced.**
  Potentially by up to 25% once the port timing and sizes are optimized. This is in process through the use of gas dynamic modeling, computer aided design and dynamometer testing.

- **Only three moving parts.**

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Projected SFC for the Compound Rotapower® Engine Based on Available Data

Figure 3, taken from NASA TM 105562, shows that NASA was able to match the SFC of RR at 0.375 lb/hp·hr for a turbo-charged and diesel fueled rotary engine. Both the NASA and RR engines used oil-cooled rotors. Figure 4 shows that using a charge cooled rotor should result in a 10% reduction in SFC versus an oil cooled rotor. Based on this reduction, the projected SFC would be 0.34 lb/hp·hr. NASA had planned to undertake a number of improvements that were projected to lead up to a further 20% reduction in SFC.

Unfortunately the NASA test program was terminated due to lack of funds. If only 50% of this projected reduction were to be achieved, the SFC would be 0.31 lb/hp·hr. for a diesel fueled version of the compound Rotapower® engine. The best SFC recorded for an automobile engine is 0.33 lb/hp·hr for the diesel fueled Audi 2.5 L TDI.

BSFC Improvement Steps: Accomplished and Potential

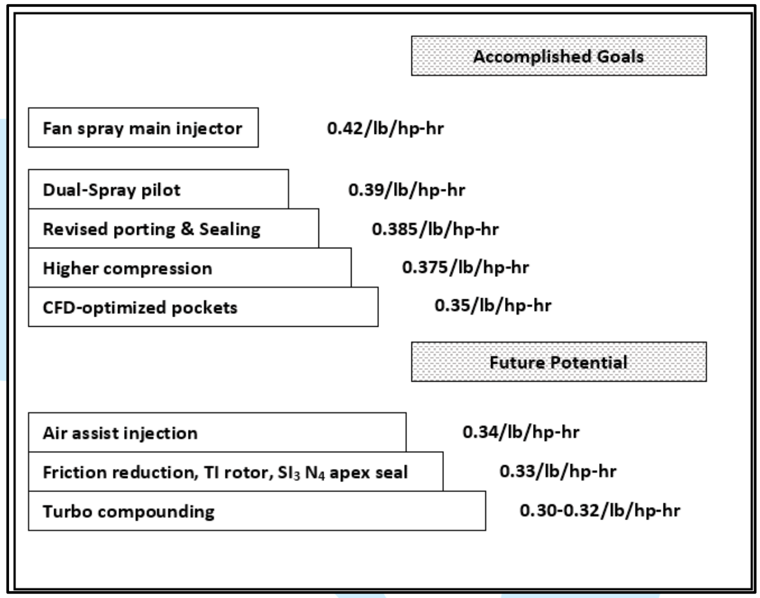

Figure 3

Comparison of Friction Loss Between Mazda 500cc and Freedom Motors 530cc Single Rotor Engines

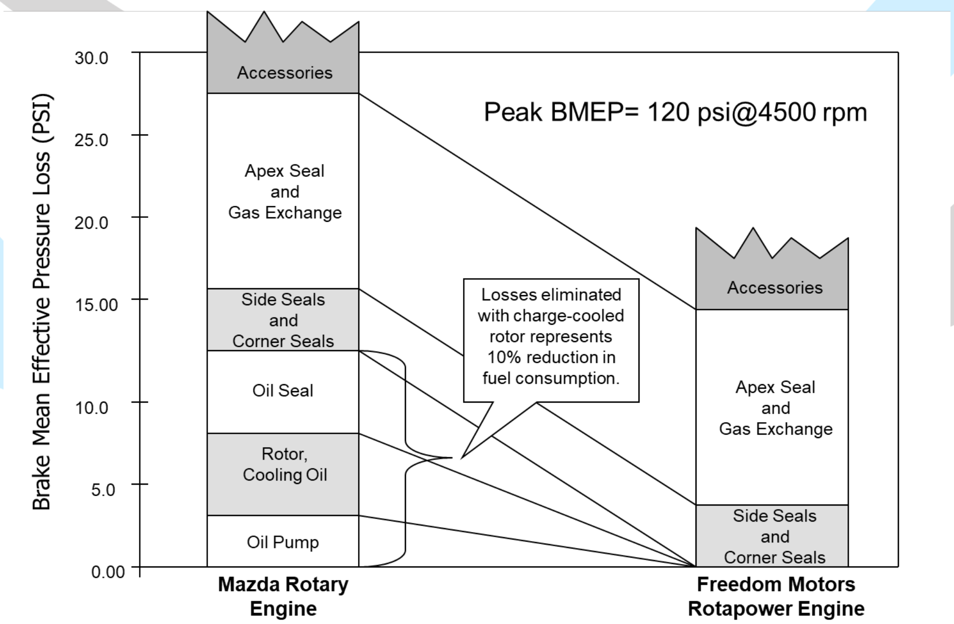

Figure 4

Market Opportunities where the Attributes of a Compounded Rotapower® (5- stroke) Engine are Uniquely Applicable

- **Powering personal AAM aircraft.** Acting as the prime power source or as a range extender for unmanned or an air-taxi powered by batteries. An often-repeated comment is "where is my flying car". The answer: "When a quiet, low cost engine is developed with a high enough power to weight ratio to make this possible". Aircraft piston engines produce about one horsepower per pound of weight. Aircraft versions of the Rotapower® engine have demonstrated a power to weight ratio exceeding three. This, together with its other attributes, makes the *longed-for* flying car possible.

- **Range extender for electric vehicles.** A compound rotary engine requires less than one-third the volume of a piston engine and has seven percent of the moving parts. Low noise, vibration, fuel consumption and emissions are attributes of a compound Rotapower® engine that are necessary in this application.

- **Powering a one-kilowatt genset**. The US Government has established that a genset engine producing one kilowatt of electrical energy produces enough energy from its exhaust and cooling to provide the hot water needs of the average US home. This $240 billion program is being implemented to place a one-kilowatt genset in every home with access to natural gas. The performance goals are: 37% thermal efficiency from the engine/generator at a noise level of 55 dba. The compound Rotapower® engine can meet this noise requirement and exceed the thermal efficiency of a piston engine powered genset. This approach results in an overall thermal efficiency above 90%.

- **Powering gensets by sourgas or biogas.** Forty percent of the world's natural gas (primarily methane (CH_4)) is contaminated by hydrogen sulfide (H_2S). This contaminated natural gas is referred to as sourgas. A second source of methane called biogas is manmade. Biogas is generated anaerobically from landfills, wastewater plants, animal manure, and as a byproduct of the petroleum industry. Biogas is more contaminated than sourgas; however, any contaminant may need to be removed at considerable cost prior to being utilized for energy production. The compound Rotapower® engine can use both biogas and sourgas as sources of energy at much less than the installed cost of piston or microturbine engines because of its lower production cost and tolerance to H_2S and silica. Compounding allows the intake pressure to be increased enough to take advantage of the very high-octane rating of biogas/sourgas which further improves its thermal efficiency and ability to use biogas with a low methane content.

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- **Powering the world motorcycle and motor scooter market.** Many countries eliminate or reduce the vehicle license fee if the engine displacement is low enough. As a result, these low powered motorcycles and scooters have poor performance. The compound Rotapower® engine can produce three times as much power as a piston engine for the same displacement. The worldwide market for engine driven motorcycles/scooters is over $125 billion annually.