

## Small-scale rotary engine power system development status

M. Swanger, D.C. Walther<sup>\*</sup>, A.C. Fernandez-Pello, A.P. Pisano  
Berkeley Sensor and Actuator Center  
BSAC/EECS #1774  
University of California, Berkeley  
Berkeley, CA 94720-1774

And

I.Y. Chan, K.D. Carabell  
ChevronTexaco – ERTC  
Chevron Oronite, LLC  
100 Chevron Way, Richmond, CA 94802

### Abstract

The liquid fueled miniature Wankel engine project is directed toward the development of a practical small-scale power generator. This power generation system is based upon an engine that has a displacement of approximately 350mm<sup>3</sup> and a designed power output of approximately 50W. Recently, the project has seen some encouraging results through design improvements in many of the system components, most notably sealing. Seal efficiency has improved from below 10% to 50%, comparable to commercially available engines. This improvement has resulted in naturally aspirated operation with high volumetric efficiency and operation on liquid fuels. These improvements have been confirmed by an increase in compression ratio and a commensurate increase in power output. In a product such as this, the unit cost is an important factor in its overall viability and the engine design reflect the need for reduced production cost to make the unit competitive with devices of similar power output. This work summarizes the development status of the program and indicates future directions with the expectation of a fully operational prototype system in place by the end of 2004.

## Introduction

The goal of this project is to develop, fabricate, and test a small-scale Wankel rotary engine to be used in an autonomous, portable power generation device. The project is ongoing and many of the overall objectives and basic design issues have been previously reported [1]. MEMS systems are being developed to monitor and control fuel delivery, engine health, and efficiency. These designs are also still in development and are expected to be integrated to the overall engine concept later in the program [2]. Liquid hydrocarbon fuels have a high energy density yet are currently not used for power generation on the smaller scales normally served by batteries. A thorough review of the issues related to combustion device development at the small scale has been previously reported [3]. Potentially, a liquid-fueled power generation device will provide higher specific energy and power than comparable batteries for long operation times.

In order for this engine development program to be ultimately successful, three key issues must be addressed: adequate sealing, ignition and the subsequent combustion event, and proper fuel delivery. All of these issues are being addressed as part of this research program and many of the designs are currently being tested [2,4,5,6]. This work addresses many of these developmental issues and testing results for this engine platform as they pertain to the eventual development of a stand alone portable power generation system.

## Experimental Set-Up

The core engine design consists of several traditional Wankel engine components, including the rotor, crankshaft, housing and endplates as well as auxiliary systems for ignition, fuel delivery and sealing. Engine testing is performed on a specially designed test stand. Each of these components will be described below and can be seen in Figure 1.

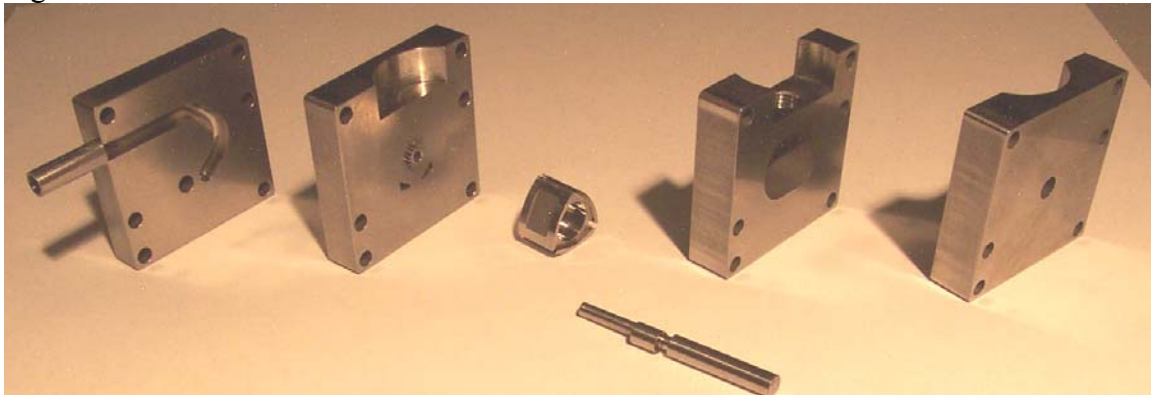


Figure 1. Exploded shot of engine components.

*Rotor* – A triangular shaped piston which houses apex and face seals and transmits power to the crankshaft through an off centerline pressure force. The rotor dimension for a majority of testing here is 12.9mm in height and 9mm in depth, which leads to the approximate 350mm<sup>3</sup> engine displacement.

*Crankshaft* – A single rotor engine has an eccentric design which accepts the transmitted torque from the rotor to a purely rotational torque outside of the endplates. The crankshaft looks like a single valve camshaft.

*Rotor Housing* – The epitrochoidal shaped internal housing that, when mated with the trochoidal rotor, contains and separates the intake stroke, compression stroke, ignition, power stroke and exhaust.

*Gears* - The rotor gear is housed within the rotor which serves to maintain engine timing through meshing with the rear gear and contact at each of the apex seals with the housing.

*End Plates* – House the intake ports and exhaust ports, and serve as axial cover plates for the engine. One of the end plates maintains the rear gear.

*Seals* – The traditional Wankel engine contains both apex seals and some configuration of face seals. The primary purpose of the seals is to separate the three chambers, contain combustion, and to insure adequate compression ratio.

Many configurations of seals have been tested throughout this work including apex seals, side seals, and face seals. Apex seals span the rotor from end-plate to end-plate at all three tips of the rotor. These seals are typically spring backed and are the primary sealing mechanism for rotary type engines of this scale. A one piece side seal is a spring backed face seal that prevents leakage from pushing past the edges of the rotor, Fig. 2 (top). This serves to complete the seal grid of each separate chamber of the rotor from apex to apex. Three piece side seals serves the same purpose as the one piece, but is made up of three individual spring backed strip seals that span from apex to apex along both sides of the rotor, Fig. 2 (bottom). This sealing mechanism is effective, however for engines of this scale, the resulting part count and assembly time is significantly larger than simpler designs.

*Ignition* – Two ignition methods can be implemented into the Wankel type rotary engine, spark ignition and glowplug ignition. Glowplug ignition is attractive for portable power generation since it requires no external power supply to maintain ignition. The catalytic surface maintains sufficient heat to remain active as one combustion event is completed and another begins. In addition, glowplugs can be utilized in the rotary platform because, in contrast to traditional piston engines, the intake charge is moved around the housing and is not constantly exposed to the ignition mechanism. Despite these advantages, the majority of testing has utilized a surface gap spark plug due to the ability to adjust ignition timing without engine housing modifications. Surface gap plugs can significantly improve engine performance on the small scale as this type of spark plug serves to reduce gas blow-by as the apex seal crosses over the spark location, and also increases compression ratio by reducing “dead volume” in the combustion chamber.

*Fuel delivery* – Several approaches have been taken to deliver precise quantities of fuel to the engine. In early testing, when sealing was ineffective to aspirate sufficient levels of



Figure 2. 1-pc. (top) and 3 pc. (bottom) Face (or side seals). Springs for each design are also shown.

air and fuel for engine operation, mass flow controllers were used to deliver a supercharged mixture of fuel and air. As sealing improved, natural aspiration was used to meter the air and gaseous fuel was delivered at atmospheric pressure either through a mass flow controller or by fuming the fuel to the venturi of a small carburetor to the intake manifold. As the scale of carburetors is reduced, pressure losses to viscous losses begins to increase in magnitude and the effectiveness of the carburetor decreases, manifesting itself as a reduced pressure drop at the throat of the carburetor.

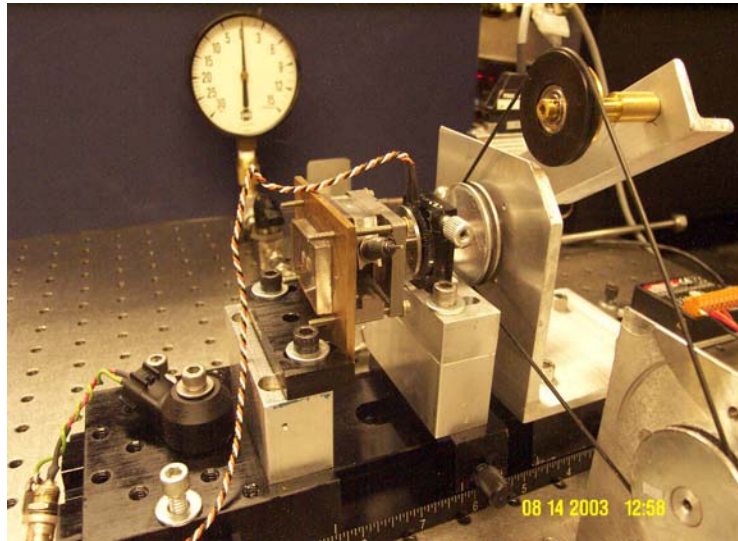


Figure 3. Engine test stand.

*Test Stand* – The test stand consists of an optical rail which aligns the electric motor / belt drive assembly, the ignition timing mechanism and the engine mounts. The electric motor initially turns the engine and can be switched to serve as an electrical generator. The power generation characteristics of the Maxon EC250 electric motor have been determined through a series of calibration steps previously noted [1]. The belt drive assembly replaced a rigidly coupled direct drive system to allow the engine speed to fluctuate due to the combustion event without the influence of a direct drive. A Newport optics rotating optical mount is used to vary the position of a hall sensor that is triggered by a magnet mounted to a small flywheel on the crankshaft. The far end of the crankshaft is mounted in a pillowblock bearing to minimize any precessing motion. The engine assembly is rigidly mounted to an optical mount to ensure alignment of each of the components.

## Results

### *Sealing*

The principal parameter which controls engine performance at engines of this scale is engine sealing or leakage flows throughout the engine. As the scale of the engine is reduced, the relative clearances (part tolerance) must be increased to maintain relative performance levels. Several approaches can be used to maintain these small clearances. In the absence of any sealing mechanisms, manufacturing tolerances must be minimized to gap dimensions of approximately 0.0005". These tolerances are readily available for simple structures, but prove to be difficult to manufacture in the unique shapes inherent to the Wankel platform. Modern CNC controls can however meet these requirements [7]. In the presence of active sealing mechanisms, the fabrication tolerance requirement is somewhat relaxed, however part count and assembly protocol become more difficult. Throughout the course of this engine development, engine sealing has been improved in a

variety of ways including part tolerance increases and active sealing structures. The leakdown test is an industry standard static engine performance metric in which a pressurized reservoir is connected to the engine at the spark plug location. A known orifice is located between the reservoir and the engine and pressures are noted in the reservoir and downstream of the orifice. In our testing, the reservoir is maintained at 60psi and the orifice has a diameter of 0.008". The orifice area is designed to have approximately the same area as the combined leakage path lengths within the engine. Leakage rates are then noted as the pressure difference between the reservoir and orifice measurements. By this method, the improvement in sealing over the time period of the development work is easily noted in Figure 4 and performance is now comparable with commercially available Wankel type engines. The impact of engine lubricants can also be easily seen. As the engine operates in the presence of liquid films, the effective sealing gap is decreased and the sealing performance increases.

Volumetric flow testing shows that the ports are not restrictive and are capable of allowing 100% displacement into the engine up to 3000 RPM. A bubble flow meter was used to determine the flowrate out of the exhaust and compared to the theoretical displacement at this speed. The amount of vacuum that was pulled at the intake was also determined. For these tests, the engine had metal apex seals with steal leaf springs, 3 piece side seals also backed by steal "wavy" springs as shown in Figure 2 (bottom). A vacuum gauge was connected to the intake tube and the engine rotated to 3500 RPM. Under dry conditions, a 16.9kPa of vacuum was noted. Under wet conditions at the same engine speed, the amount of vacuum was increased to 33.9kPa.

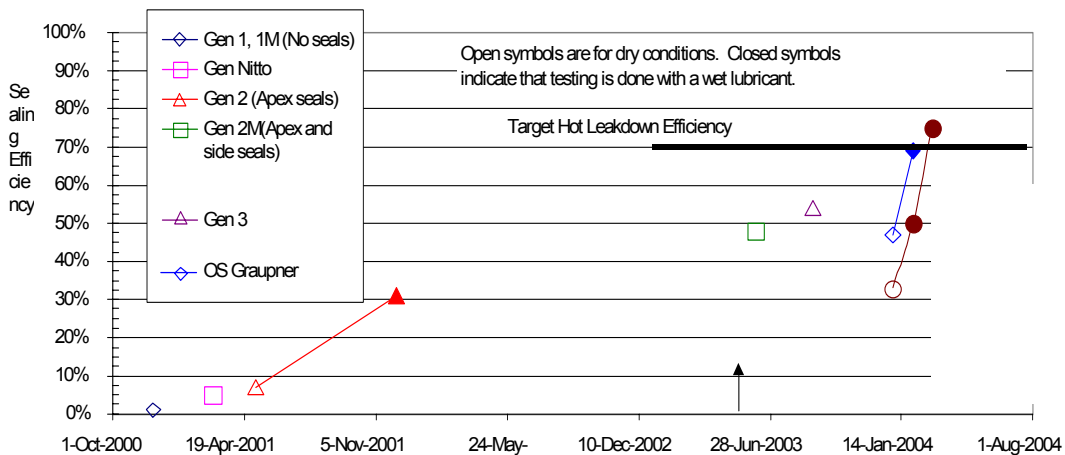


Figure 4. Sealing chart that measures leakdown rates as a function of time. The OS Graupner is a commercially available Wankel-type engine. The data shown to the far right is a 5hp Nitto design.

### Operating conditions

Engine operation under a variety of sealing conditions and fuel delivery approaches has produced significant temperature rises in both the engine block and exhaust, demonstrating that combustion is taking place. In the absence of combustion (as determined by not firing the spark plug and noting that the compression ratio is currently insufficient to auto ignite the fuel air mixture), the engine block temperature reaches a range of temperatures from 40-70°C for operating speeds up to 20krpm, with the majority

of this heating due to friction. 'Exhaust' temperatures under the same conditions do not reach any higher than 45°C.

Engine housing temperature increases, under glowfuel operation have reached 105°C. Large scale testing of uncooled Wankel engines has indicated peak temperatures of 235°C. This observation and the measured sealing levels indicate that the small scale Wankel engine described here is not operating at the designed compression ratio and hence the combustion event and in turn the housing temperature have not been optimized. For gaseous fuels, the exhaust temperature reaches maximum levels at an ignition timing of 15deg.BTDC. This indicates complete or more stable combustion in the rotor combustion pocket. When the ignition timing is retarded in increments of 5 deg. back to TDC, the exhaust cools to around 10°C above ambient temperature. When operating on hydrogen/air mixtures, if the ignition timing is further retarded beyond TDC, 5deg.ATDC as an example, there is external combustion in the exhaust pipe as evidenced by audible signatures and high exhaust temperature excursions. When operating with liquid fuels, the results differ slightly. If the ignition timing is set at TDC, there is unburned liquid present in the exhaust pipe indicating incomplete combustion in the rotor chamber. These observations are consistent with moderate scale Wankel engines.

Operation using pure methanol as fuel, the highest housing and exhaust temperatures and audible signatures are noted at 15deg.BTDC. Hydrogen makes the highest temperature and audible combustion at TDC. All else being maintained the same, these observations are consistent with the reaction rates of the two fuels. Hydrogen, with faster kinetics, has a shorter combined ignition delay and reaction time.

Quantifying temperature based on type of fuel and has up to this point been erratic. This is due in part by the fact that the engine has not actually stabilized and operated consistently for sufficient periods of time to collect data. During the testing period that resulted in the previously noted 4 watts of power with hydrogen [1], it was discovered that the engine's porting had excessive overlap that would cycle in and out of stable combustion and prevented stable engine temperatures. These results were convoluted by the presence of pre-ignition as well. Pre-ignition also causes the temperature to fluctuate, as the combustion is not constant. The pre-ignition was discovered to have been caused from the spark plug location at the minor axis. In the Wankel type engine, it has been problematic to locate the plug here since there is still high pressure gas from the expansion stroke that is introduced into the fresh incoming intake mixture which is ignited prior to ideal rotor position - creating negative work. The port and plug locations have been moved to avoid these difficulties.

Temperature changes as a function of ignition timing have been stable for operation with both gaseous and liquid fuels. These results utilize a surface gap spark plug in the ideal position after the minor axis, known as the leading position. The repeatable results under these conditions are that both the exhaust and engine temperature increase 20-25 C with each 5deg. of ignition timing advance beyond TDC up to 15deg.BTDC. For example, with an ignition timing of 0deg.TDC on a liquid fuel, the engine housing temperature reaches 45 C. If the timing is advanced to 5deg.BTDC the housing and exhaust temperature both rise 20-25°C to 65-70°C. Further advances in timing beyond 15deg.BTDC cause the temperatures to decrease.

Audible signatures for engine operation also are used to determine the impact of spark timing. As the spark timing is advanced beyond 15deg.ATDC (After Top Dead



Center), significant noise level increases are noted. This is consistent with large-scale engine operation [8].

Recent results have also been very encouraging based on several damaged engine parts. In one recent test using a glow plug, glow fuel (10% Nitromethane, Methanol and Castor Oil), and carburetor, the engine speed unexpectedly increased from 8 kRPM to 12 kRPM at a rate exceeding the control system (manual adjustment of the carburetor fuel jet). The engine speed was noted to increase followed by a period of decreased performance and eventually the engine seized. These events resulted in a bent crankshaft, distorted stationary gear (see Fig. 5 below), and severely damaged rotor gear. It appears that a significant pressure rise was developed during the combustion stroke as noted by the location of the bend over gears (about 2 o'clock location). Unfortunately, the gear end of the crankshaft was too small (2.5mm diameter) to support the radical rise in pressure from that event. It is postulated that the damaged gears lead to improper engine timing which resulted in the involute shaped impact patterns from the rotor gear at the tip of the rear gear. With further testing and development, in the areas of fuel delivery, ignition, and sealing, the level of performance is expected to reach projected levels.

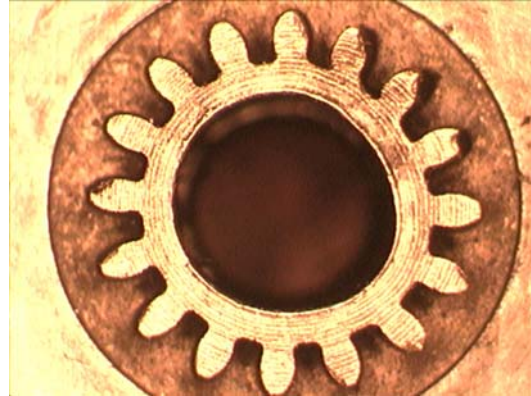


Figure 5. Rear gear showing rolled over involute gear teeth (2 O'clock position), impact marks and noncircularity of shaft clearance hole after engine seizure and crankshaft failure.

### Conclusions and Future Work

Engine performance has increased on both liquid and gaseous fuels as observed by better internal sealing, increased operation temperatures and internal pressures. By increasing seal efficiency the engine has gone from operation in a supercharged state to natural aspiration, and improved port design and location have given us 100% volumetric intake at the lower speeds. With the development of the surface gap spark plug the results are less gas blow by and higher compression ratio. The results of these incremental improvements have been encouraging and positive – despite the setbacks caused by component failure. These failures have led to significant understanding and have proved vital for future engine design. The results noted for these engines are for conservative engine designs and significant modifications. Based upon these findings, engine designs that incorporate many of the necessary design features have recently been completed. We anticipate that that further improvements to sealing, ignition, and fuel delivery within these new designs will yield greater power output and efficiency.

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