ROTAPAC POWER MODULE

The Revolutionary Power Source for the Plug-in Hybrid Automobile

Product Introduction

The US has an urgent need to eliminate its dependence on Middle East oil. Since this region supplies only a small portion of the total oil consumed by the US auto industry, an increase of 3.25 miles per gallon would achieve this independence.

The modest mileage increase offered by present hybrid automobiles would require that they be sold in very large numbers to significantly reduce this oil dependence. However, recent battery developments make the plug-in hybrid electric car (PHEV) possible which could triple the effective miles per gallon achieved by hybrids like the Toyota Prius or Honda Insight. GM has proposed a PHEV they named Volt where the engine is used only as back-up for trips longer than 40 miles. This approach is attractive since charging the PHEV from the electrical power grid is equivalent to paying less than one dollar per gallon of gasoline. Replacing the majority of one year's US automobile production by PHEV's would eliminate the need for Middle East oil. The most significant design problem to creating a practical PHEV is finding the internal space to accommodate the large battery required for a 40 mile range together with the back-up engine/generator. In the GM Volt the proposed back-up piston powerplant is just as large as that in the Toyota Prius with its battery powered range of only 3 miles.

Moller International (MI) has, under government contract, developed and demonstrated that using its Rotapower rotary engine together with a state-of-the-art generator can reduce the usual space required for a piston engine power supply by over 80%. MI proposes to use its proven technology to create a 25 kilowatt self contained power module called Rotapac. This small back-up module will include all cooling, muffling and controls and would provide the PHEV with a number of advantages:

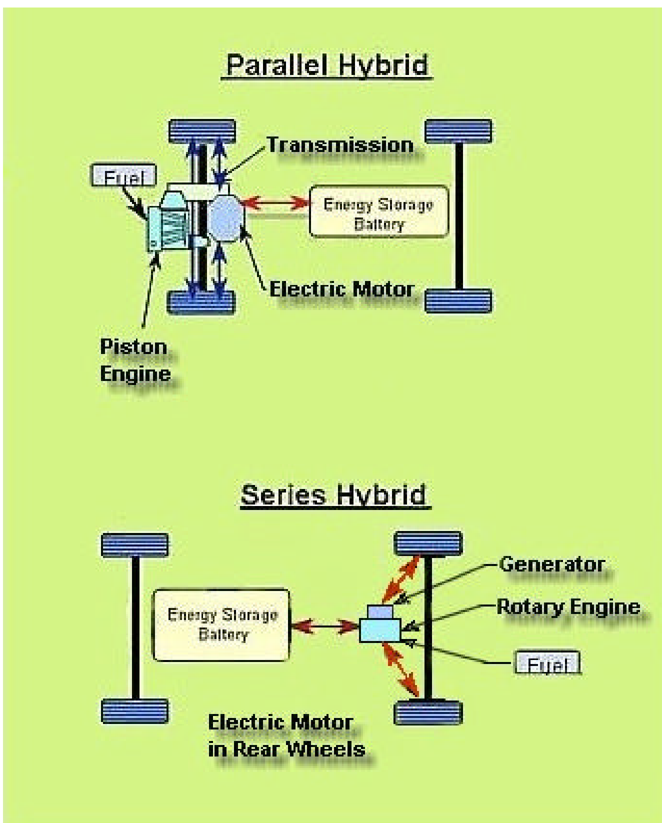
- Module size is comparable to that of a small suitcase
- Additional modules can be added for larger vehicles or for use in mountainous terrain or when towing a load
- Can be serviced or replaced in minutes
- Running the engine when plugged in at home provides sufficient electrical power to meet the emergency needs of a large house including heating and air conditioning.

The Rotapac power module makes possible a 25 kilowatt electrical power supply that is two man portable. Such a unit is not available in today's market and would be useful for a large number of mobile applications in addition to the plug in hybrid automobile.

Status of Hybrid Automobiles

Series versus Parallel Drive Systems: Hybrid cars have historically evolved in two different forms depending on the expected trip profile of their use. For short trips with considerable stops and starts (like perhaps a city bus) a ***series drive*** is a better choice. In this design an engine drives a generator, which charges a battery and/or powers an electric drive motor. The system is simple, but loses conversion energy in the generator, battery and motor. It is, however, much better at recovering energy during slowing down through the relatively simple implementation of regenerative braking where the vehicle's kinetic energy is converted back to stored electrical energy. The series system relies more on the battery and would typically use a smaller, simpler engine either running at constant speed or stopped, as required.

For longer distances at higher speeds the ***parallel drive*** system is more efficient. It is the system currently used in the Toyota Prius and Honda Civic Hybrid. This system requires a multi-speed transmission and a complicated engine that can operate over a wide RPM band. It is also more difficult to use regenerative braking with these systems because of their smaller battery capacity. The parallel system relies mostly on direct engine power to the wheels and uses the relatively small (as compared to a series system) battery as a buffered power source. Range on the battery alone is limited to about three miles.



When batteries were limited in their capacity they served to compliment the automobile engine. Their use resulted in a smaller engine, some regenerative braking and allowed the engine to turn off at stoplights and during low speed. All of this resulted in improved mileage, particularly in stop and go traffic, although limited battery storage required the engine to do most of the work. The introduction of lithium-ion batteries changed that paradigm. The proposed GM-Volt uses the fact that the average automobile travels only 28 miles/day and so they designed their hybrid to be able to travel 40 miles on batteries alone. Their hybrid will have a one-liter engine that can produce enough power to deal with occasional extended operation in mountainous terrain. It will also have a plug-in capability for recharging. For the majority of daily trips the engine will never operate and the car could average the equivalent of over 150 miles per gallon of gasoline depending on local electrical energy costs. Even in modest numbers this plug in electric hybrid vehicle (PHEV) could quickly reduce our dependence on foreign oil since it only takes a 3.25 MPG increase in the fleet average to make the U.S. independent of all Persian Gulf oil.[1]

The GM-Volt is a fundamental shift from the engine-dominated hybrid. Its back-up series drive system is a change from the much more expensive and complex parallel drive system used by Toyota and Honda. However one can be fairly certain that both Toyota and Honda are moving in this same direction and will probably produce PHEVs well before GM.

In a parallel drive system, engine efficiency through a broad power and rpm band is critical because the engine must be capable of maintaining thermal efficiency (good fuel economy) over a wide range of operating conditions. To maintain this efficiency these engines may include variable valve timing, variable intake length and variable compression. They also benefit from a turbo or supercharger in order to reduce the engine size while designing for fuel efficiency over a broad power band compromises the maximum fuel efficiency that can be achieved. Furthermore to reduce engine power, size, and cost, the number of cylinders is reduced. Thus the GM-Volt proposes a three-cylinder engine, which will generate high radial and torsional vibration levels.

In a PHEV, power band is not important while volume available for batteries is critical and therefore engine size and weight dominate. In this case the engine can be operated at a specific RPM which greatly simplifies its design and allows a higher peak thermal efficiency much closer to peak power. This results in a much smaller engine for the same horsepower.

The Rotapac – A Rotary Engine Driven Power Module

The rotary engine based on the Wankel principle has always been considered a brilliant design with enormous potential, however it has not generally succeeded as a prime mover for the automobile (See History, Appendix A). However for many applications, including the PHEV, the rotary engine's narrower power band is not a liability while its small size, low weight, low cost and freedom from vibration are major assets. MI has developed a number of different engine sizes and demonstrated them in many applications (See Appendix B). The rotary engine is particularly well suited to powering a generator because of its ability to operate effeciently at higher RPM reduces the generator's size. MI intends to integrate its Rotapower® rotary engine with an alternator/generator to create a small, self-contained power module suitable for installation in a PHEV. This module will include muffling, cooling and controls.

TWO LEADING QUESTIONS

1. What in general makes the rotary engine a good candidate to power the electrical source for a series type hybrid car?

2. What in particular makes the Rotapower rotary engine the ideal powerplant for a self-contained power module for a PHEV?

Mazda Rotary Engine

The only volume production rotary engine on the market today is the Mazda rotary. Compared to the piston engine it is less than two-thirds the size for the same power. Unlike the piston engine, the rotary design is capable of being completely inertially balanced. Anyone who has driven a Mazda car will confirm its freedom from vibration. With only three moving parts compared to 37 for a three cylinder 4-stroke piston engine it is also much simpler. The rotor in the rotary engine rotates at one third the output speed. This allows the Mazda rotary to operate efficiently at high RPM (it is red-lined at 9000 RPM) which is one of the reasons it is substantially smaller than the 4 stroke piston engine. On the other hand, its specific fuel consumption is higher than the best four-stroke piston engine partly because it requires a separate complicated oil cooling system for its rotors.

Rotapower Rotary Engine

Moller International's Rotapower engine eliminates the separate oil cooling system by using the incoming fuel-air mixture to cool the rotor in what is called charge cooling. This greatly simplifies the engine so that it weighs less than one-half the weight of the Mazda engine for the same horsepower with less than 40% the volume. Details on how this is achieved are provided in a paper prepared by MI in 1999 that addressed the Rotapower engine's competitive position at that time.[2] In a recent development by MI, much of the normally wasted exhaust energy is recovered through a unique patent pending design of its engine (compounding).

Previous Use of the Rotapower Engine in Series Hybrid Automobile

In the mid 1990's Moller International (MI) received a contract from the Defense Advanced Research Project Agency (DARPA) to develop a series hybrid car using its Rotapower engine.[3] MI had convinced DARPA that the public would pay the extra cost of a hybrid car if it also provided high performance.

MI designed a series hybrid with special spiral wound lead-acid batteries that had been recently developed by Bolder Technologies. These batteries, acting like super-capacitors, could be rapidly charged and discharged. This allowed both rapid acceleration and complete regenerative braking. MI's hybrid car was able to accelerate from 0-60MPH in less than 6 seconds and was projected to achieve well over 50 miles per gallon of gasoline. Unfortunately before the fuel economy could be documented the special spiral wound lead-acid batteries failed miserably. The contract's budget did not allow for the replacement alternative of super-capacitors. Dr. Andrew Burke from the Institute of Transportation Studies (ITS) at the University of California at Davis was a consultant on the project and had shown in an analysis of MI's hybrid that it would achieve over 54 miles per gallon of gasoline with a <u>non-compounded engine</u>. The following figure shows that even without compounding, MI's hybrid was superior to any hybrid today except the parallel hybrid with a lean burn engine. The parallel drive is unnecessarily complicated for a PHEV.

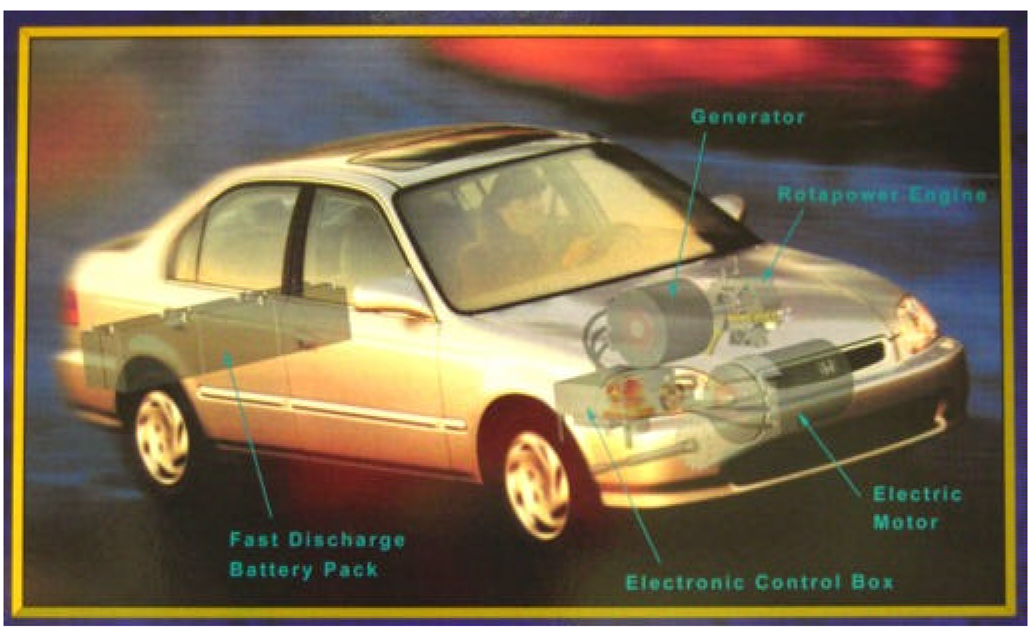
The fuel economy on different driving cycles for various hybrid powertrain designs and engines for compact passenger sedans*

	0-60 mph sec	0-50 mph sec	mpg ECE-EUDC	mpg FUDS	mpg FedHW
Conventional Internal Combustion Engine (ICE)	7.9	5.8	27.2	27.6	41.2
Series hybrid* with Rotary engine and capacitors	7.6	6.2	-----	50.0	54.1
Parallel hybrid+ with standard gasoline and capacitors	7.8	5.9	46.1	45.1	45.5
Parallel hybrid with standard gasoline engine and Nickel metal hydride batteries	8.7	6.7	43.5	41.5	45.1
Parallel hybrid with a lean-burn gasoline and capacitors	8.4	6.3	58.8	58.7	60.4

***Series hybrid vehicles: rotary engine 23kW, generator 20kW, electric motor 110kW, energy storage 50 kg.**

+Parallel hybrid vehicles: engine power 85kW, electric motor 18kW peak, energy storage 25 kg.

The fuel economy values used for the diesel engine vehicles are for the European combined driving cycle (ECE-EUDC); for the gasoline engine vehicles, the fuel economy was calculated by averaging the fuel economies for the US Federal Urban (FUDS) and the Highway cycles.



Moller International Series Hybrid Car

The following information has been extracted from “Hybrid Vehicles with Batteries and Ultracapacitors in China” authored by Andy Burke, Institute for Transportation Studies, University of California, Davis, 2005:

Rotary Engines in hybrid vehicles

- Best used in <u>series hybrids</u> with the generator connected directly to the rotor shaft
- Small size of the rotary engine makes packaging much less difficult than with a reciprocating engine
- Rotary engines operate best at high rotational speed and in a relatively narrow speed range and have efficiencies comparable to standard engines
- Rotary engines are smooth and quiet compared to other engine types
- The cost of the rotary engine in volume production should be less than other engine types
- Two-cycle engine size and cost with 4-cycle engine efficiency and low emissions

Rotary engines from Moller International

- Paul Moller and Moller International (Davis, California) have been world leaders in the development of the modern rotary engine since 1985
- The Moller rotary engines are superior to the Mazda engines in several respects: rotor cooling, lubrication, engine friction, and rotor surface coatings
- The efficiency of the Moller engines is the same as conventional engines at most torque and RPM conditions
- Emission tests of Moller rotary engines have shown the capability to meet California ULEV standards in vehicles without exhaust after-treatment
- Production equipment is available at Moller International for limited production of engines

Rotapower Engine Emissions

In earlier tests carried out in conjunction with ITS and witnessed by members of the California Air Resources Board (CARB) the Rotapower engine using gasoline as a fuel achieved hydrocarbon, carbon monoxide, and nitrous oxide emission levels well below those required to meet the Ultra Low Emission Vehicle (ULEV) standards for California. This was accomplished without exhaust after-treatment (catalytic converter) and had not been achieved previously with any other engine. Recently MI carried out similar tests using ethanol as a fuel because it has proven to be the ideal fuel choice, including its much more effective cooling of the rotor (high heat of vaporization). Using ethanol resulted in emissions well below the Super Ultra Low Emission Vehicle (SULEV) California standards again without exhaust after-treatment. The results of the earlier tests with gasoline and the recent tests with ethanol are tabulated as follows:

ULEV Data

(Rotapower engine running on gasoline)

Unburned hydrocarbons (HC)
.6 ppm = .0635 gm/hp-hr = .016 gm/mi (40% of ULEV std.)

Carbon monoxide (CO)
372 ppm = 1.24 gm/hp-hr = .31 gm/mi (18% of ULEV std.)

Nitrogen oxide (NO_X)
100 ppm = .65 gm/hp-hr = .16 gm/mi (80% of ULEV std.)

SULEV Data

(Rotapower engine running on ethanol)

Unburned hydrocarbons (HC)
.5 ppm = .0043 gm/hp-hr = .002 gm/mi (2% of SULEV std.)

Carbon monoxide (CO)
9 ppm = .03 gm/hp-hr = .013 gm/mi (1.3% of SULEV std.)

Nitrogen oxide (NO_X)
3 ppm = .016 gm/hp-hr = .007 gm/mi (35% of SULEV std.)

Emission levels are below the California Super Ultra Low Emissions Vehicle (SULEV) standards when adjusted for an automobile traveling at a steady 70 miles per hour.

Rotary Engine Fuel Consumption

The rotary engine has an enormous number of advantages over both the 2 and 4-stroke piston engine but historically has provided superior fuel consumption only over the 2-stroke engine. In 1992 a NASA study evaluated the potential of the rotary engine to achieve lower specific fuel consumption.[4] They successfully demonstrated that with turbo-charging the rotary engine was able to achieve a specific fuel consumption of .375 LB/HP HR or a thermal efficiency of 37%. This is equal or better than the best turbo-charged piston engine using gasoline. Because the energy in an engine's exhaust exceeds that necessary to drive a turbo-charger, considerable energy is normally lost. NASA goes on to show that extracting a larger portion of this energy would lead to a thermal efficiency between 43.5% and 46.5 % compared to the standard gasoline engine at 32%. A multi-stage turbo charger that not only supercharged the intake but was connected to the output drive shaft could accomplish this and make it competitive with the turbo-charged diesel engine (the gold standard as the most energy efficient internal combustion engine).

However turbo-charging alone is expensive, while increasing the size and complexity of the turbo-charger together with a gearbox to reduce the 200,000-RPM turbine to 5000-RPM would be prohibitively expensive. That is why this theoretically attractive engine was never developed.

Compound Rotapower Engine Achieves Superior Fuel Consumption

In the standard two-rotor rotary engine, the rotors work in parallel doing the same thing. Two rotors are normally used in order to smooth the instantaneous torque (vibration) and reduce exhaust noise. MI's Rotapower® engine generates this same low torsional vibration with two rotors on the same shaft, but each rotor performs a different function (rotors work in series rather than in parallel).

In this configuration the first rotor compresses the charge (fuel/air mixture) prior to sending it to the second rotor where the charge is further compressed prior to combustion. The combusted gases, by expanding in the second rotor, provide output power before exiting under significant pressure into the expansion cycle of the first rotor where the additional expansion extracts most of the remaining energy from the combustion gases. The exhaust then exits the first rotor with little pressure (noise). This design is in the patent pending phase and a first generation version has run successfully in dynometer tests. The results, although preliminary, are as follows:

- Exhaust noise reduced by 93% (20dbA)
- Exhaust temperature reduced by 50% (900º F)
- Specific fuel consumption reduced (27% projected reduction)
- Improvements identified for a 2nd generation engine and addressed in MI's pending patent.
- Second generation engine underway

Rolls Royce in 1992 created a compound rotary engine by stacking the first rotor on top of the second rotor and then gearing them together. The added gearing together with the oil-cooled rotors made this design much heavier, larger and more expensive than a charge cooled engine with both rotors on the same shaft. The Rolls Royce engine however did achieve a very respectable 39% thermal efficiency despite not being optimized.

The following figure generated earlier by Dr. Burke at ITS tabulates thermal efficiency of the non-compounded MI Rotapower engine versus various alternatives. The additional column was added by MI assuming the minimum performance predicted by NASA.

Maximum engine efficiency as a function of power fraction (P/Pmax)

Engine Efficiency (%)

Power fraction P/Pmax	Moller Rotary (Non-Compound)	Standard Saturn Gasoline engine	Honda Insight Lean-burn engine	Audi Turbocharged Diesel engine	**Moller Compound Rotary (Projected)**
0.2	23.0	28.6	37.7	38.5	**31.4**
0.3	29.0	32.1	37.7	39.7	**39.4**
0.4	31.9	32.7	37.2	39.7	**43.4**
0.5	31.9	32.7	36.3	38.5	**43.4**
0.6	30.7	30.0	35.3	37.0	**41.8**
0.7	29.2	26.7	33.1	35.4	**39.7**
0.8	29.0	26.0	28.5	31.2	**39.4**
1.0	25.7	25.3	27.0	27.8	**35.0**

It is important to compare the power output characteristics of the compound Rotapower engine versus the turbo-charged diesel. The Rotapower engine achieves essentially the same thermal efficiency as the turbo-charged diesel at twice the P/Pmax ratio. This means that the Rotapower engine could have one half the displacement or size for the same power at the same specific fuel consumption.

The Rotapower engine achieves and maintains its low specific fuel consumption at substantially higher RPM than the piston engine. This allows the hybrid’s generator/alternator to be much lighter.

How the Rotapower Engine Compares to 4-Stroke, 3-Cylinder Piston Engine as A Power Module Candidate

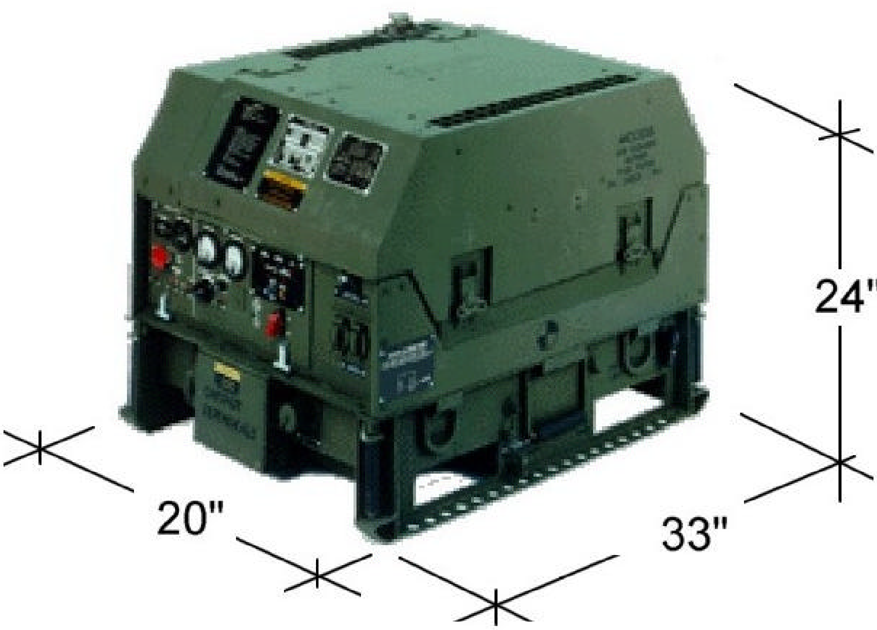
- Cost is approximately 40% less than that for comparable (based on OMC data of rotary engine production costs versus alternatives).[5]
- Much less vibration
- Much cooler exhaust temperature.
- Much lower exhaust noise.
- Specific fuel consumption lower.
- Multi-fuel capable and works particularly well with ethanol.
- 3 moving parts versus 37.
- Satisfies California ULEV standard on gasoline.
- Satisfies California SULEV standards on ethanol.
- Is much simpler, lighter and smaller.
- Efficiency at higher RPM allows substantially smaller alternator/generator.

The Opportunity Exists to Revolutionize Portable Power with the Rotapac Power Module.

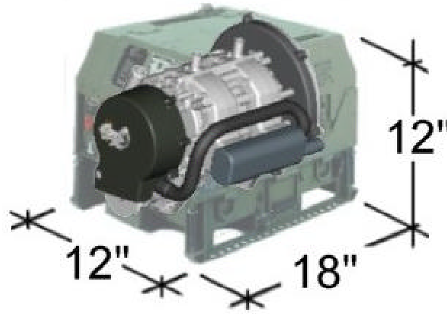
It is proposed that a new company be formed and funded to produce and distribute self-contained power modules as the electrical power source for the PHEV. The nominal power capability suggested is 25 kilowatts consistent with the studies carried out at the Institute of Transportation Studies (ITS) as well as the experience with MI's series hybrid.

This small power module provides the following advantages over a 4-stroke piston driven electrical generator/alternator:

- 32% of the weight
- 16% of the volume
- Much lower emissions
- Better fuel economy
- Allows the use of more than one module to meet specific performance requirements for larger vehicles or operations in mountainous terrain or towing a trailer, etc.
- Module can be removed or replaced in minutes
- Module can provide power directly to the home in the case of an emergency
- Module is generic enough to be marketed for any application where its self-contained electrical power generating capability can be utilized



Scaled from Gillette GPN-150EC 25kW
375 lbs 9.2 ft ^{3}



Rotapac 25kW
120 lbs 1.5 ft ^{3}

Appendix A

History of the Rotapower Rotary Engine

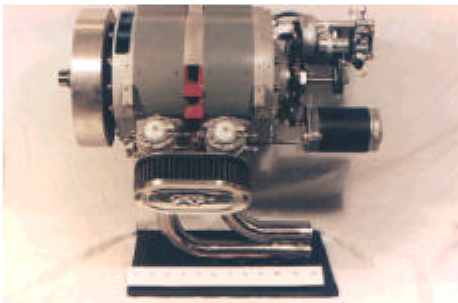
The Rotapower rotary engine developed by Moller International (MI) is based on earlier patents by Dr. Felix Wankel. Wankel's engine garnered great enthusiasm for its attributes when it was first demonstrated. In the 1960's over 30 companies began developing rotary engines for their products which included outboard motors, motorcycles, chainsaws, airplanes and most importantly, automobiles. Virtually every automobile company began a program. During this same period MI's predecessor company M Research began researching the potential of the rotary engine. Unfortunately in the mid 1970's there was major interruption in fuel supplies concurrent with government mandated improvements in emissions. Re-tooling for a new engine that was at that time not particularly fuel efficient while addressing emissions became too risky for the auto industry. In addition, Mazda Motors which was the first company to volume produce rotary engine powered automobiles (RX-2) had a side seal problem that allowed the rotor cooling oil to enter the combustion chamber. This required Mazda to recall tens of thousands of their automobiles for what was in effect a major overhaul. Mazda forged ahead and by 2006 their RX-8 model won the Sport Car of the Year Award; however the rotary engine was never the ideal candidate as a prime mover for the automobile because it operates best over a narrow RPM band.

The only other company to successfully produce a rotary engine was Outboard Marine Corporation (OMC) which began mass producing an air-cooled snowmobile rotary engine in the early 1970's. OMC, at that time, was the world's leading producer of outboard motors, and anticipated changing their marine line to use rotary engines. This was motivated by concern that 2-stroke engines which powered all their products, would fail the proposed emission standards. OMC developed production ready models for their marine line at a cost according to the division manager, of over $200 million in 1970 dollars. This program established that the rotary engine could be built for a cost virtually identical to their inexpensive 2-stroke engines. When the administration in Washington changed in 1980, emissions ceased to be a high priority and OMC dropped their production plans. Between 1983 and 1989 MI acquired the entire rotary engine assets of OMC.

In 1997 MI also acquired the assets of Infinite Engines, a NASDAQ listed company which with MI's help had developed a rotary engine for the marine and snowmobile markets. By this time MI and its predecessor companies (M Research and Moller Corp) had developed a number of patented improvements to the rotary engine. With the acquisition of the engine technology from OMC and Infinite Engines, MI incorporated these patented improvements into their proven engine designs.

Appendix B

Pictures of Products Utilizing the Rotapower Engine



Aircraft Engine (1060cc)

Commercial Engine (27cc)

Industrial Engine (650cc)

Mini-Jet Boat (1060cc)

Jetski 1300cc

Hybrid fuel-electric vehicle (530cc)

All Terrain Vehicle - ATV (530cc)

Unmanned Aerial Vehicles (530cc)

Industrial Engine (150cc)

[1] Lovins Amory "Energy Security Facts", Rocky Mountain Institute, 2003.

[2] Moller, Paul "The Operation and Performance of the Charge Cooled Rotapower Rotary Engine Oil Cooled Rotor Rotary Engines". MI Paper No. 9912-1999.

[3] Hybrid Vehicle with High Performance Rotary Engine DARPA/CALSTART Contract No. RA-94-24

[4] Willis, Edward and McFadden, John "NASA's Rotary Engine Technology Enablement Program-1983 through 1991", NASA.

[5] Comments of George Miller, General Manager, Outboard Marine Corporation, 1985. Later confirmed by John Sheldon, previous Director of OMC's Rotary Engine Advanced Performance Program, 2004.