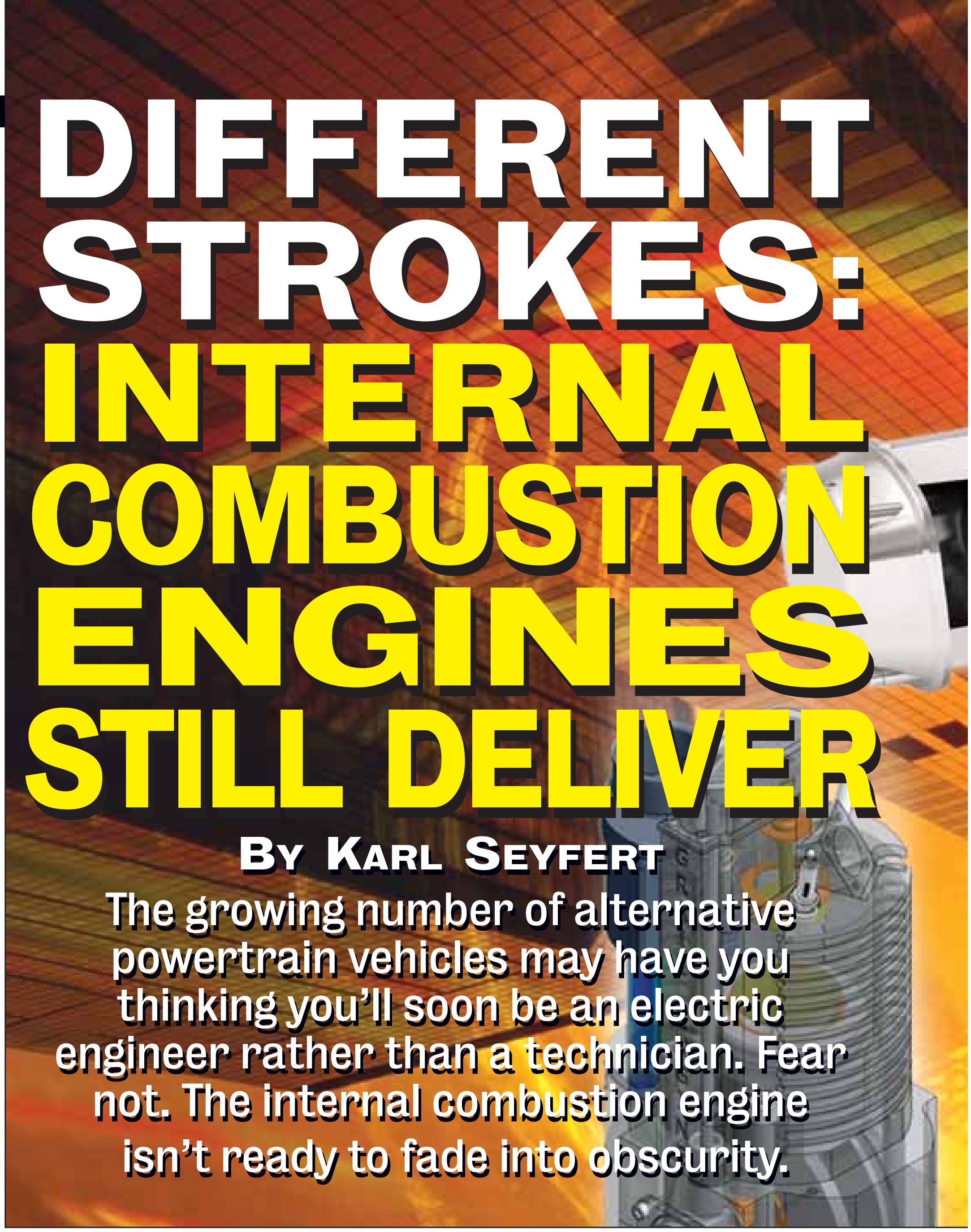


DIFFERENT STROKES: INTERNAL COMBUSTION ENGINES STILL DELIVER

By Karl Seyfert

The growing number of alternative powertrain vehicles may have you thinking you'll soon be an electric engineer rather than a technician. Fear not. The internal combustion engine isn't ready to fade into obscurity.

Predictions regarding the demise of the internal combustion engine (ICE) have a long history. The steadily growing number of hybrid and full electric vehicles on the road has only added fuel to the fire, so to speak. But while naysayers have been trying to decide how many more years the ICE has left, engineers and visionaries at several different companies have been looking for ways to extend its life well into the future. They've accomplished this by completely reimagining how an ICE works and what it looks like.

In this article, we'll examine the new technologies that have been developed by these companies. Simple inline or V-type piston engines are definitely not included in this group. It's anyone's guess how many (or if *any*) of these designs will ever end up in a mass-produced vehicle that you'll see in your shop. For now, it's interesting to see how far you can go with air, a little bit of fuel and a great deal of ingenuity.

EcoMotors International (*www.ecomotors.com*) has developed an opposed-piston, opposed-cylinder (OPOC) engine that will run on a number of different fuels, including gasoline, diesel and ethanol. The original OPOC engine design has a long history dating back to the first decade of the last century, when it powered French Gobron-Brillié passenger cars. The design was later used on Fairbanks Morse submarine and locomotive engines, Grey Marine and Detroit Diesel engines and German Junker aircraft engines during World War II.

The EcoMotors OPOC engine is a two-stroke, horizontally opposed, twin-bore, four-piston design. There are two pistons in each cylinder bore. The inner set of pistons is directly attached to the crankshaft and they work in much the same way as those in a traditional reciprocating-piston engine. The outside set of pistons is attached to the crankshaft via long, titanium connecting rods that are tied to a bearing at the back of each piston. The outside pistons mirror the motion of the inner pistons, moving toward the crankshaft as the inner pistons move away from it.

Intake and exhaust are handled similarly to a conventional two-stroke diesel engine—an external air-charger (supercharger or turbocharger) forces air into the cylinder through ports in one side of the cylinder sleeve. As the pistons move, the ports are covered and the air is compressed between the two converging pistons. Fuel is directly injected and the mix can be fired by spark or compression ignition, depending on the fuel used. Exhaust is eliminated through ports on the other side of the cylinder bore when they're uncovered at the end of the piston travel.

Because the combustion event occurs in the middle of the cylinder bore between two movable pistons, there's more surface area for the combustion pressure to affect. Consequently, more of the energy released by combustion is converted into mechanical force. This results in an engine whose power density is higher than a traditional engine (more than one horsepower per pound of engine weight).

This design configuration also eliminates the need for the cylinder head and valvetrain components of conventional engines, offering a compact and simple core engine structure. In fact, there are 50% fewer parts than on a conventional engine. Due to the reciprocating action of the pistons, all engine forces counteract each other, for low noise and vibration.

If more power is needed, additional modules can be connected together, then separated at will via an electronic clutch mechanism. This variable displacement feature allows power output to be doubled when needed for larger vehicles, then decoupled when no longer needed, to provide significant fuel savings. The manufacturer claims an engine family that is lighter, more efficient and


Photoillustration: Harold Perry; images: EcoMotors Intl., Grail Engine Technologies, Doyle Rotary Engine & Thinkstock

economical than conventional engines, with lower exhaust emissions.

Pinnacle Engines (*www.pinnacle-engines.com*) has taken a different approach to the opposed-piston (OP) engine design. Paired pistons facing each other inside common cylinders are still utilized, but there are two crankshafts instead of one. They're on the outside of the horizontally opposed engine layout, and drive the paired pistons toward each other in unison. The two crankshafts are linked to each other to keep everything synchronized.

Like the EcoMotors OPOC engine, Pinnacle Engines' OP design does not require a cylinder head or valve gear. And like many things automotive, if you look back far enough, you'll discover that this design has been tried before (World War II aircraft engines).

What's different is the company has taken this four-stroke, spark-ignited (SI), opposed-piston, sleeve-valve architecture and added something called the Cleeves cycle, named for Monty Cleeves, the company's founder and chief technical officer. Control of the engine's sleeve valve allows the engine to provide Otto cycle combustion (constant volume combustion) or diesel cycle combustion (constant pressure combustion), depending on operating conditions and the fuel available.

In addition to eliminating the need for conventional valve gear, half the total number of ignition and injection components are required compared to a conventional boxer engine, because two pistons share a common bore. The engine's modular design is easily scalable, depending on the required power output.

The design is said to be compatible with most fuels, including gasoline, diesel, natural gas, propane and their biofuel replacements (e.g., ethanol). Additional efficiency improvements can be achieved by incorporating variable valve timing, a variable compression ratio mechanism, direct injection and turbocharging, according to the manufacturer. The company claims fuel-efficiency improvements of 30% to 50%. By closely controlling the thermal cycle, exhaust emissions are also claimed to be reduced.

Achates Power (*www.achatespower.com*) has developed an opposed-piston, two-stroke diesel engine that uses two reciprocating pistons per cylinder. Like other opposed-piston designs, the Achates Power engine does not need cylinder heads, which are a major contributor to heat losses in conventional engines. Ports in the engine's cylinder walls replace the poppet valves and friction-creating valvetrains of conventional engines. Intake ports at one end of the cylinder and exhaust ports at the other are activated by the piston motion and enable efficient air scavenging.

The company claims its proprietary cylinder and piston designs achieve improvements in combustion efficiency and oil consumption to meet the most stringent emissions regulations. In conjunction with the thermal efficiency advantage inherent to opposed-piston engines, its designs are said to realize significant reductions in fuel consumption over conventional four-stroke compression ignition engines. The use of two-stroke compression ignition will permit the use of second-generation renewable fuels derived from soybeans, biomass, algae and other sources.

The Scuderi Group (*www.scuderigroup.com*) has developed an engine using a split-cycle design that divides the four strokes of the combustion cycle between two cylinders. One cylinder handles the intake and compression strokes (the compressor cylinder), while the other is responsible for the power and exhaust strokes (the expander cylinder).

By splitting the four strokes between the two cylinders, the engine is able to produce one combustion cycle per crankshaft revolution, just like a two-stroke engine. Also, by separating the compression cylinder from the power cylinder, the size of the compressor cylinder can be reduced to eliminate some of the negative work of the compression stroke. The engine's output is the difference between the positive work produced by the power stroke and the negative work consumed during the rest of the cycle.

An exhaust-driven turbocharger forces the maximum volume of air into the compressor cylinder. Once it's been further compressed by the compressor piston, the air is transferred between the paired cylinders via a crossover passage. Fully variable, outward-opening crossover valves control the flow of compressed air from the first cylinder to the second. At the appropriate time, fuel can be direct-injected into the expander cylinder or port-injected into the charge air during transfer into the expander cylinder via the crossover passage.

As the compressed air is transferred to the expander cylinder from the crossover passage, sonic flow and high turbulence enhance fuel/air mixing and promote stable, robust combustion. The resulting flame speed is unusually fast, with a 10% to 90% burn duration of only 12° crank angle. The extremely fast combustion and late fuel addition provide a high knock avoidance characteristic, and rapid expansion during combustion reduces NO_X emissions—significantly below conventional engine levels—without using exhaust gas recirculation (EGR).

The Miller cycle was originally developed to increase the thermal efficiency of a supercharged, four-stroke engine by making the compression stroke shorter than the expansion stroke. This was accomplished by employing a valve timing strategy that closed the intake valve early, before the piston reached its bottom dead center (BDC) position. The early timing strategy effectively shortened the compression stroke without shortening the expansion stroke.

By closing the intake valve early, however, the valve event can't be optimally timed to deliver maximum volumetric efficiency, and a portion of the available displacement can't be used. Also, when closing the valve early, the valve event occurs when piston velocity and air velocity are high, as are the associated pumping losses.

Rather than shifting the intake valve close (IVC) timing, extended expansion in a Scuderi split-cycle engine is achieved by reducing the fixed displacement of the compressor cylinder relative to the fixed displacement of the expander cylinder. By differentially sizing the cylinders, IVC is timed at a period of low piston velocity, where an optimum trapped mass condition can be attained and pumping losses can be avoided.

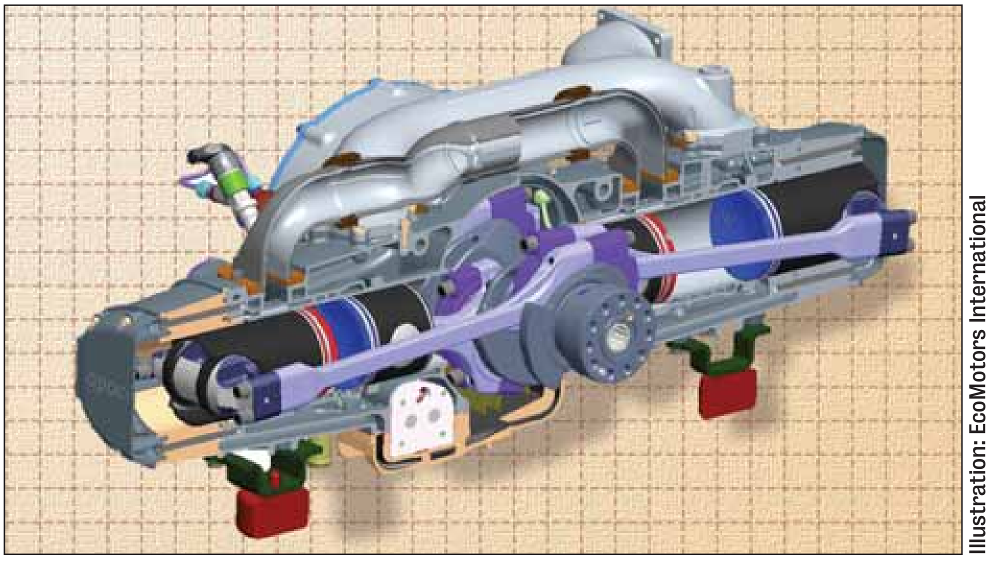


Illustration: EcoMotors International

Fig. 1 This cutaway illustration reveals the EcoMotors engine's opposed-piston, opposed-cylinder design, which dispenses with the need for a cylinder head and all of the related valve gear. The extra-long pair of connecting rods allow the outer pistons to mirror the movement of the inner pistons.

The Scuderi split-cycle engine also employs a compressed air storage tank that stores compressed air energy produced by the compressor cylinder during periods of low demand and uses it to produce power during periods of high demand. This technology can be used to reduce engine size and weight, increase specific power and torque and reduce fuel consumption and emissions.

According to the manufacturer, unlike any other reciprocating ICE technology, the Scuderi engine's split-cycle technology decouples the compression processes from the expansion (combustion) processes, enabling compression independent of expansion and expansion independent of compression. With the processes decoupled, energy produced by one process can be stored until needed by the other. Power is available when needed, or stored when it isn't needed.

In the Firing and Charging Mode, the compressor and expander cylinders are enabled, and the air storage tank is recharged while the expander cylinder is firing. Air flows to the air storage tank and expander cylinder.

In the Air Expander and Firing Mode, the compressor cylinder is disabled, and

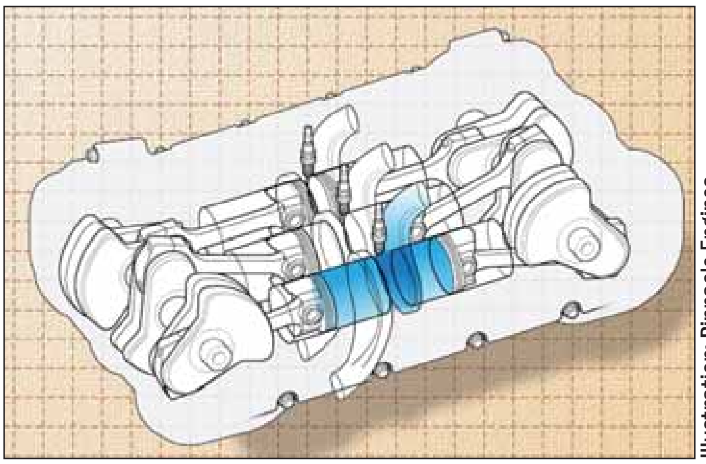


Illustration: Pinnacle Engines

Fig. 2 The Pinnacle engine design utilizes paired, opposed pistons inside common cylinders. Like the EcoMotors design, this engine has no cylinder head or valve gear. The modular design is easily scalable, depending on the required power output, and is claimed to be compatible with most fuels.

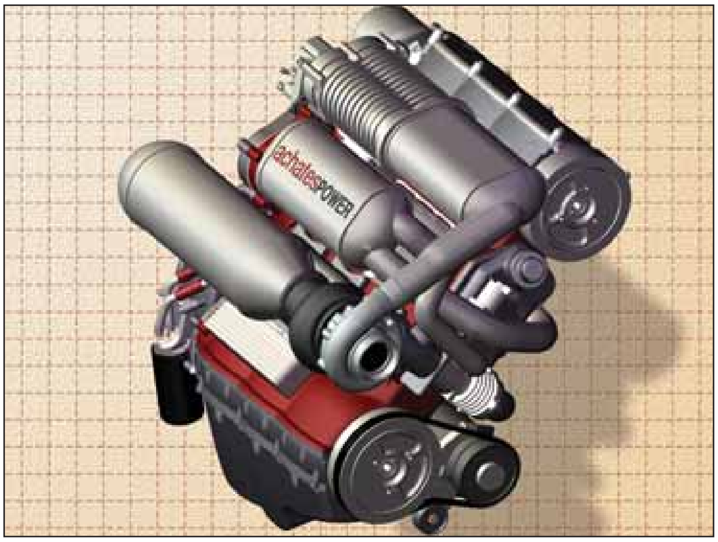


Illustration: Achates Power

Fig. 3 The Achates Power design is an opposed-piston, two-stroke diesel engine that uses two pistons per cylinder, working in an opposing, reciprocating action. The company claims significant reductions in fuel consumption over four-stroke compression ignition engines. Two-stroke compression ignition will also permit the use of second-generation renewable fuels derived from soybeans, biomass, algae and other sources.

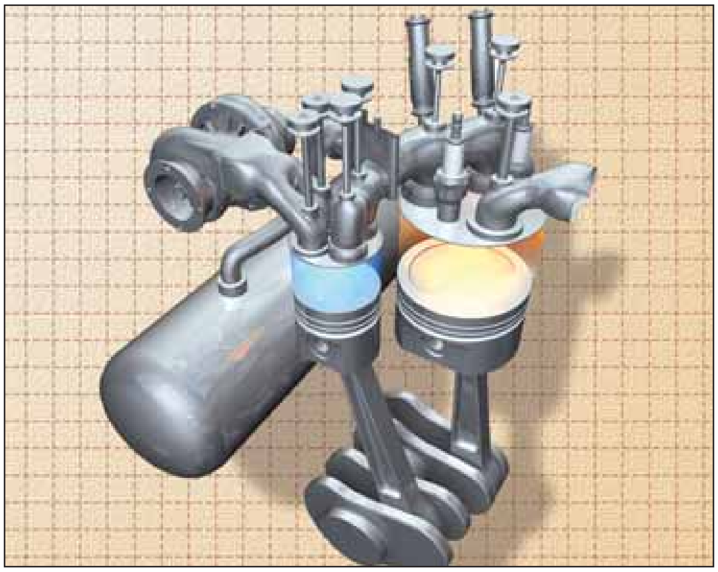


Illustration: Scuderi Group

Fig. 4 In the Scuderi Group's split-cycle engine design, the smaller cylinder and piston are responsible for intake and compression, while the larger cylinder and piston handle the power and exhaust strokes. An exhaust-driven turbo aids in cylinder filling and an external air tank stores unused compressed air for supplementary power when needed.

high-pressure air for firing is released from the air storage tank, without airflow to or from the compressor cylinder.

In the Air Compressor Mode, the expander cylinder is disabled, and the compressor cylinder recharges the air storage tank during downhill operation, braking and deceleration. Air flows to the air storage tank, without fuel injection or ignition firing.

In the Air Expander Mode, the compressor cylinder is disabled, and high-pressure air is released from the air storage tank to power the engine, without fuel injection or ignition firing.

Doyle Rotary Engine (*www.doylerotary.com*) has designed and built (as its name implies) a rotary engine. But the Doyle engine isn't anything like the Wankel rotary engines used in many Mazda vehicles over the years. Rather, it's a variation on the radial engine, like those found on many propeller-driven airplanes of the past. A radial engine is conventional in that the crankshaft spins while the cylinders remain stationary. The reverse is true of a rotary engine. The crankshaft is fixed and the crankcase and cylinders spin around it. Rotaries of this design were used in Gnome biplanes during World War I. They also powered Adams-Farwell automobiles, which were built in relatively small quantities between 1905 and 1912.

The Doyle engine takes this rotary engine design and literally turns it on its head. In a conventional rotary engine, the tops of the pistons face outward, and the connecting rods are connected to the central crankshaft. Each cylinder has its own cylinder head, intake and exhaust valves and ignition system. In the Doyle engine, the tops of the pistons face the center of the engine. The connecting rods point outward and are attached to the external case. The external case, pistons and cylinders all rotate around a central combustion chamber on an eccentric. As the cylinder case rotates, the eccentric causes the pistons to go up and down to produce power.

Photo: Doyle Rotary Engine

Piston tops on the Doyle rotary engine face inward. The connecting rods point outward and are attached to the external case. The external case, pistons and cylinders all rotate around the central combustion chamber on an eccentric. A side cover has been removed here to reveal the paired cylinders used in the engine's split-cycle design.

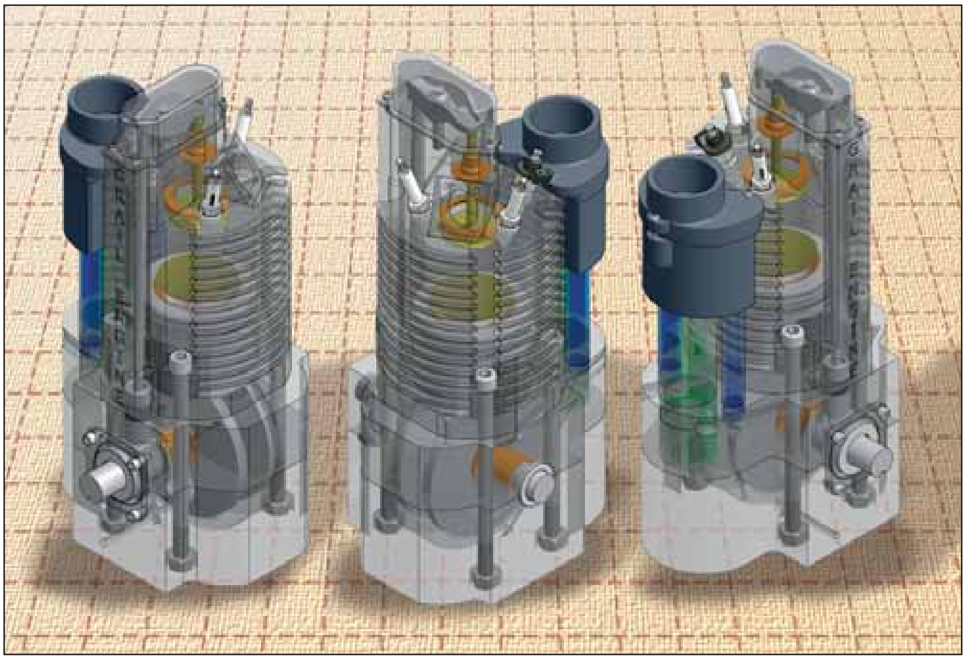
To add to the complexity, the Doyle engine is also a split-cycle design. There are two sets of pistons—one set handles intake and compression, the other handles power and exhaust. This would seem to add up to a lot of spinning metal, but the company claims that the rotational mass will actually be less than in a conventional engine of similar power because the external case is constructed of aluminum.

The Doyle engine has no intake or exhaust valves. A port at the inward-facing end of the cylinders allows gas transfer into and out of the cylinders and the central combustion chamber that's shared by all of the cylinders. A single spark plug handles ignition. Mazda rotary engine apex and rotor seals are used to seal the rotating parts.

This design can be applied to engines of varying size and displacement. Doyle has built a prototype engine with 12 cylinders and a 4.2L displacement. Paired sets of cylinders and pistons can also be stacked together to produce larger engines. Doyle has most recently reduced the number of cylinders to produce a 6-cylinder prototype.

In a conventional four-stroke engine, each piston delivers a power stroke once every two crankshaft revolutions. The Doyle split-cycle design makes it a four-stroke engine, with each power piston producing a power stroke on each crankshaft revolution. So on the 12-cylinder prototype, there are six power strokes per revolution. The company has dubbed this the Doyle cycle.

As you would expect, the company claims several advantages for its design. The split-cycle design allows one row of pistons to perform the intake and compression (IC) strokes while the other row performs the power and exhaust (PE) strokes. The central combustion chamber separates these two rows. This layout means the IC pistons and cylinders can be designed differently from the PE side. There's no need to fire before top dead center (TDC), so fuel can burn for a longer duration and more completely in the combustion chamber.



Illustrations: Grail Engine Technologies

Fig. 5 These cutaway illustrations show the Grail Engine Technologies design from different angles. The two-stroke, spark ignition engine employs an intake valve located in the center of the piston to transfer intake air from the crankcase to the cylinder. Fuel is injected directly into the cylinder.

In a conventional engine, each combustion chamber burns slightly different from the others. This is because of differences in operating temperatures and intake and exhaust lengths. In the Doyle engine, each cylinder uses the same combustion chamber. This increases the consistency in power between each cylinder, leading to an engine that runs smoother and has consistent wear characteristics for each component.

Eliminating the valvetrain means less energy is lost due to friction, Also, unlike conventional valves, the ports in the Doyle engine open and close instantly. This allows the port to remain open longer and to remain at full flow much longer than in a conventional valvetrain. This advantage is most noticeable at higher rpm, when the efficiency of conventional valvetrains begins to drop. Eliminating the valvetrain also gets rid of about a hundred moving parts, and removes the possibility of blown head gaskets, cracked cylinder heads, camshaft wear, bent or dropped valves or broken timing belts.

Lower NO_X and hydrocarbon emissions are also claimed, primarily due to the engine's split-cycle design. On a conventional engine, preignition temperatures are high because the fresh air being pulled in during the intake stroke enters a cylinder that has just exhausted extremely hot gases. The peak temperatures are increased as the ignition timing is advanced. Firing before TDC results in the piston compressing the mixture that has just been ignited. Compressing the air adds to the combustion temperature. NO_X results from the combustion temperatures remaining at a very high temperature for a long duration.

In the Doyle engine, fresh air is introduced into a relatively cool cylinder that isn't responsible for combustion. This leads to lower preignition temperatures. The fresh air is then compressed and transferred to the central combustion chamber, where fuel is injected and the mixture ignited. Firing after TDC decreases the peak combustion temperatures.

Hydrocarbon emissions arise from unburned fuel leaving the engine via the exhaust. The Doyle engine allows the fuel to burn within the combustion chamber and then in the power cylinders. Allowing a longer burn time is said to decrease the amount of unburned fuel (hydrocarbons) exiting the engine.

None of the engine designs we've covered so far could be classified as "normal" in the conventional sense. But what follows takes us even further off the well-traveled path of internal combustion engine design. With a name like **Grail Engine Technologies** (*www.grailengine.com*), it's probably safe to assume that things are going to be interesting.

The Grail engine is a two-stroke design that consists of a single exhaust valve, three spark plugs and a direct fuel injector, all located at the top of the cylinder. A single intake valve is located within the piston. A precompression chamber houses a one-way reed valve. Intake air travels through the vent-to-piston ports, through crankcase, the piston intake ports, then through the piston valve.

Compression takes place within the reed valve air box, the precompression chamber, the vent-to-piston ports, the piston intake ports and the crankcase. As the piston travels upward, a vacuum is created beneath it. Fresh air enters via the intake air box through the one-way reed valve and fills the external precompression chamber, vent-to-piston ports and piston intake ports with fresh air.

Compression occurs within the cylinder as the piston travels upward. At TDC, direct injection occurs, followed by a single or multiple ignitions. This forces the piston down into the cylinder, compressing air in the engine crankcase, external precompression chamber, vent-to-piston ports and piston intake ports.

Just prior to BDC, the exhaust valve opens via a standard cam/pushrod mechanism or electromechanical valve control. Exhaust gases exit via the exhaust valve opening at the top of the cylinder. Compressed fresh air enters the cylinder via the piston valve, which forces out the final exhaust. As the piston travels past BDC, the exhaust valve and piston valve close and the cycle repeats.

Adjusting the pressure within the external precompression chamber via a servomotor or equivalent allows control of engine volumetric efficiency over a range of engine rpm.

The company claims two other developments in engine design. The first is known as forced semi-homogeneous charged compression ignition (FS-HCCI). The second is the Grail cycle, which is a combination of one type of ignition or homogeneous charged compression ignition that simultaneously operates in the Miller cycle. According to the company, the Grail engine has the potential to be the first two-stroke engine that does not exhibit cross-contamination of fuel and oil. This results in lower emissions, yet produces more power and torque while using less fuel than larger engines.

Cross-contamination in a direct-injected two-stroke engine occurs when the piston and rings move across the intake and exhaust ports of the cylinder wall. The oil that lubricates the piston, cylinder wall and rings enters the combustion chamber exhaust and intake. If the amount of oil in this area is reduced to maintain emissions as well as the evacuation of the cylinder for clean combustion, premature wear and/or high particle emissions may result. Grail claims its engine does not suffer from these issues.

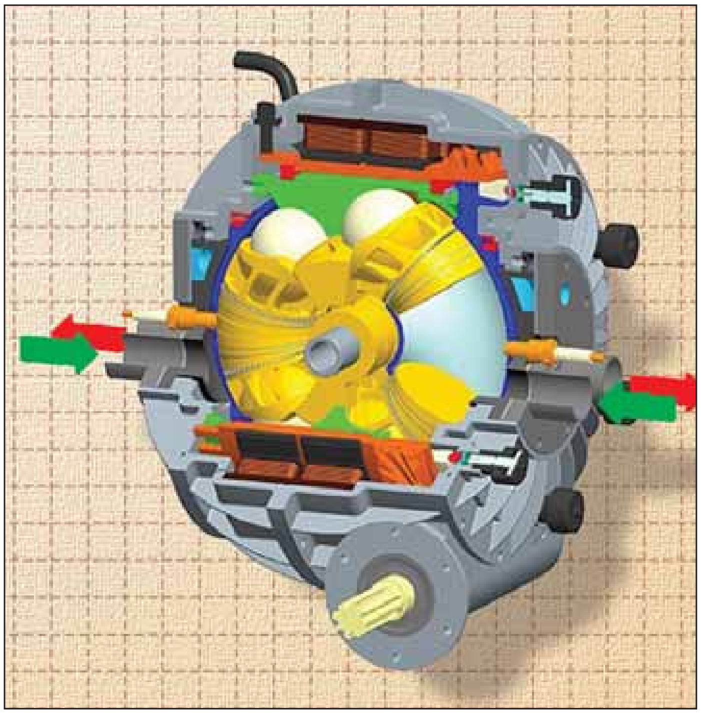


Illustration: Innomot AG

Fig. 6 The Hüttlin spherical engine is a swing-piston design that incorporates a swashplate to control the movement of the paired pistons. Shown here in its range extender configuration, the engine incorporates a generator and power takeoff. Extra-large ball bearings follow tracks in the swashplate on the inside of the sphere, opening and closing the gap between the paired pistons as the internal parts rotate. This allows the engine to generate electricity and/or drive the power takeoff.

I've saved what is probably the most unorthodox engine design for last. The **Hüttlin Spherical Engine** (*www.innomot.org*) shares some of the technology previously discussed—like opposed pistons—but it's unlike the other designs in almost every other respect. The Hüttlin Kugelmotor (spherical engine) is named for its inventor, Dr. Herbert Hüttlin, who has been working on this and other engine designs for more than 20 years.

Describing the very unconventional Hüttlin engine with words is a real challenge, which is probably why the company's website relies heavily on so many animations to tell its story. In this design, the combustion energy generated during the power stroke is directly converted into a rotary movement. There is no conventional crankshaft to be found anywhere in the design.

An aluminum spherical housing contains a piston rotor turning in two large-ring roller bearings. The rotor is equipped with curved, cylindrical chambers to receive two pairs of opposed pistons. Two hollow guide balls are used for each piston pair. These balls roll on both guide surfaces of the curved element, which is arranged in an orthogonal, longitudinally centered position on the system axis and is firmly attached to the housing. As the pistons and combustion chamber assembly rotate, the guide balls guide the pistons through the back & forth rocking motion of the four-stroke Otto engine cycle.

The company sees a wide range of uses for this engine. Several configurations have already been developed and tested, including a hybrid range extending generator, an electric motor and compressor in a single casing and a home power source to be combined with solar and thermal collectors. It can also be used in combination with a wind turbine to produce electrical energy and pressurized air.

The hybrid range extender configuration is particularly intriguing. The engine could be used to produce electricity for an electric vehicle, to supplement its batteries when they become depleted. Coupling the engine directly to the vehicle's drivetrain would allow supplemental propulsion when needed as well as regenerative braking to further replenish the batteries. With the engine's combustion function disabled, its otherwise unused compression could also aid vehicle braking.

All of the companies behind the unique engine designs described in this report believe they have what it takes to revolutionize the transportation industry. Since none of this new technology happens to include the ability to see into the future, we're probably going to have to wait a few more years to find out whether any of them are right. Regardless of the outcome, it's refreshing to see how many different methods can be em

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