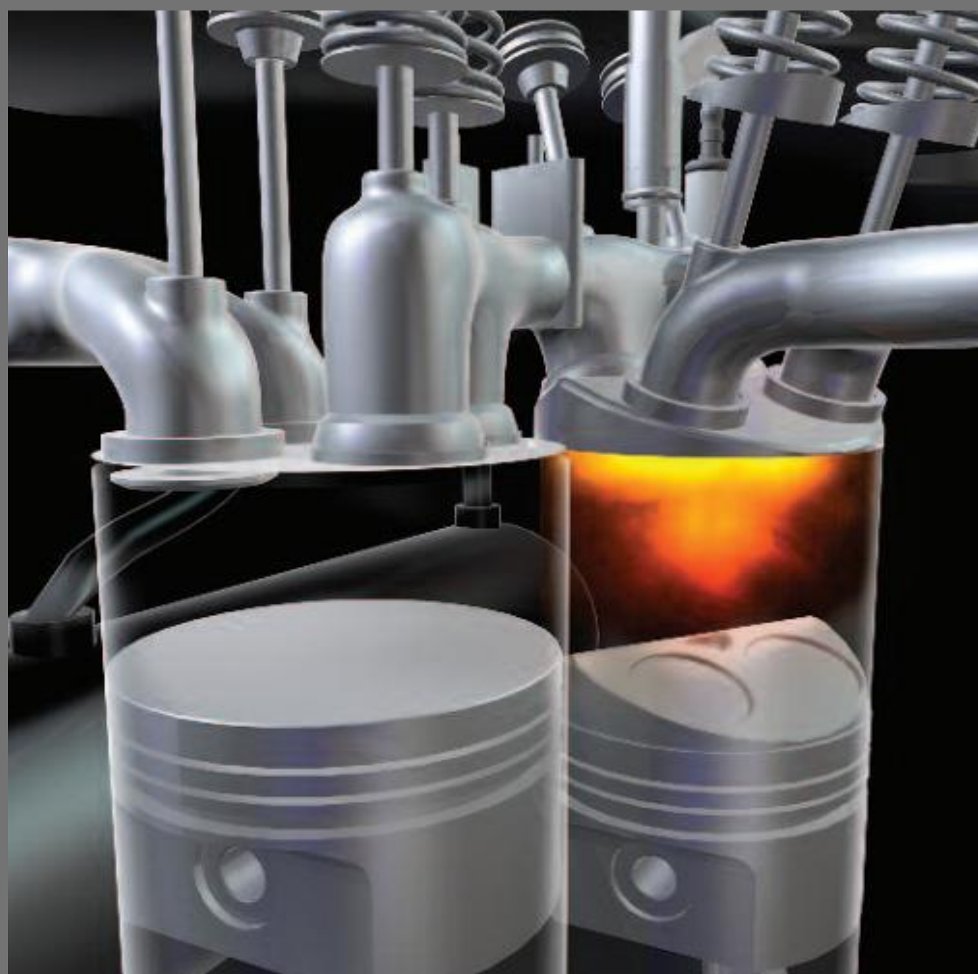
TITLE

SPLIT-CYCLE ENGINES

B.E. MECHANICAL

Split-cycle engines separate the four strokes of intake, compression, power and exhaust into two separate but paired cylinders. A split-cycle engine is really an air compressor on one side with a combustion chamber on the other.



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1. INTRODUCTION:

The **split-cycle engine** is a type of **internal combustion engine.**

Design

In a conventional **otto cycle** engine, each **cylinder** performs four strokes per cycle: intake, compression, power, and exhaust. This means that two revolutions of the **crankshaft** are required for each power stroke. The split-cycle engine divides these four strokes between two paired cylinders: one for intake/compression and another for power/exhaust. Compressed air is transferred from the compression cylinder to the power cylinder through a crossover passage. Fuel is then injected and fired to produce the power stroke.

History

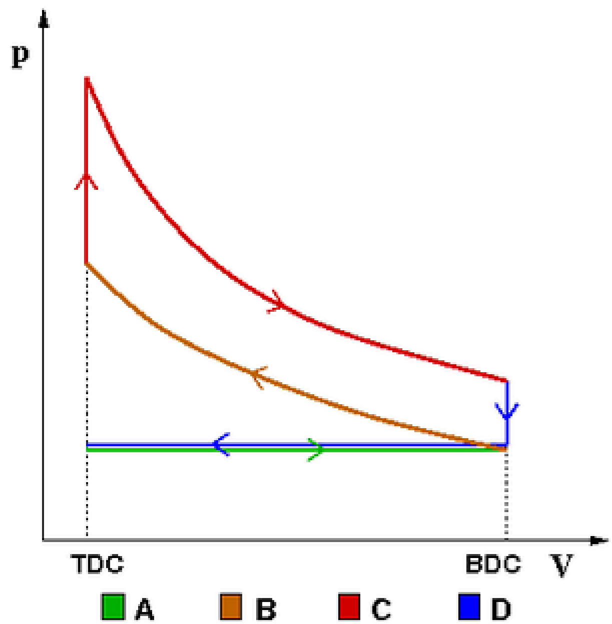
- The Backus Water Motor Company of **Newark, New Jersey** was producing an early example of a split cycle engine as far back as 1891. The engine, of "a modified A form, with the crank-shaft at the top", was water-cooled and consisted of one working cylinder and one compressing cylinder of equal size and utilized a **hot-tube ignitor** system. It was produced in sizes ranging from 1/2 to 3 horsepower (2.2 kW) and the company had plans to offer a scaled-up version capable of 25 horsepower (19 kW) or more.

- The **Twingle engine** is a two stroke engine that also uses a displacer piston to provide the air for use in the power cylinder. This was patented in 1912.

- The **Scuderi Engine** is a design of a split-cycle, **internal combustion engine** invented by the late Carmelo J. Scuderi. The Scuderi Group, an engineering and licensing company based in **West Springfield, Massachusetts** and founded by Carmelo Scuderi's children, said that the prototype was completed and will be unveiled to the public on April 20, 2009.

- The **TourEngine™** is a novel opposed-cylinder split-cycle **internal combustion engine,** invented, patented and under development by Tour Engine Inc. The unique and patented opposed-cylinder configuration of the TourEngine™ allows minimal dead space and superior thermal management. The first prototype was completed on June, 2008.

1.1] <u>BASIC OTTO CYCLE:</u>



The idealized four-stroke Otto cycle **p-V diagram**:

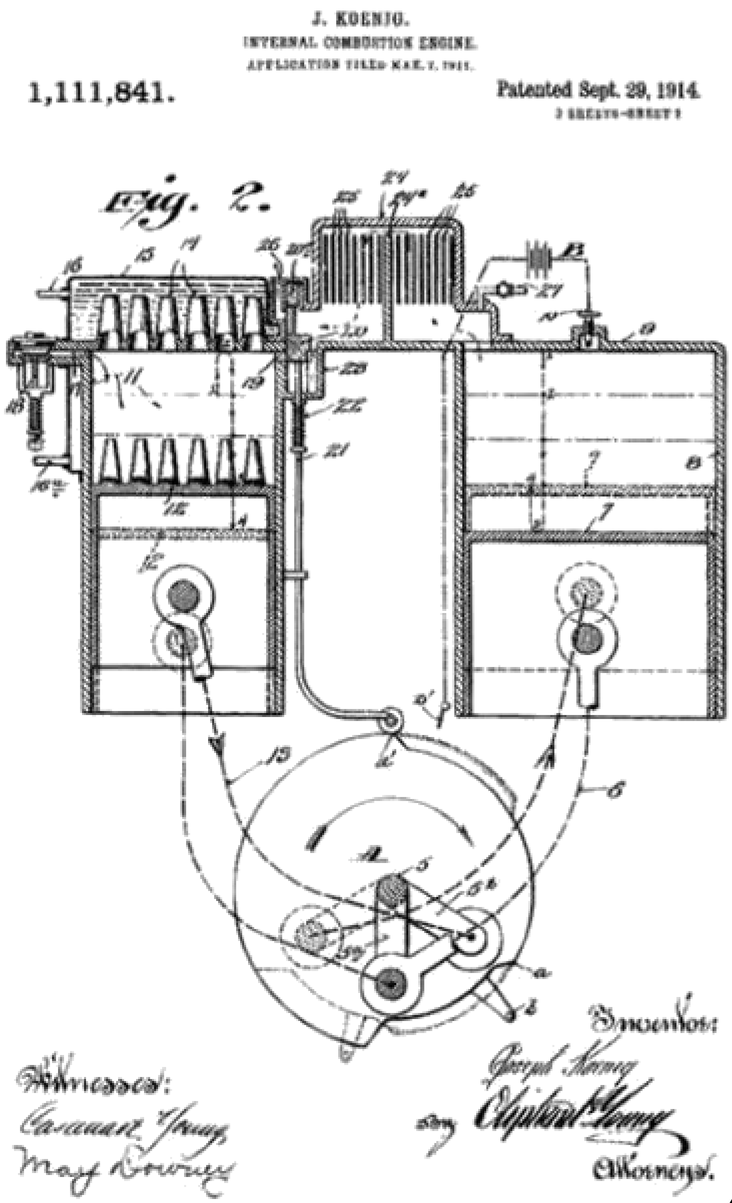
The intake (A) stroke is performed by an **isobaric** expansion,
followed by the compression (B) stroke, performed by an **adiabatic** compression.
Through the combustion of fuel an **isochoric process** is produced, followed by an adiabatic expansion, characterizing the power (C) stroke.
The cycle is closed by an isochoric process and an isobaric compression, characterizing the exhaust (D) stroke.

2. SCUDERI SPLIT- CYCLE ENGINE:

2.1] What is a split-cycle engine?

Split-cycle engines separate the four strokes of intake, compression, power and exhaust into two separate but paired cylinders. The first cylinder is used for intake and compression. The compressed air is then transferred through a crossover passage from the compression cylinder into the second cylinder, where combustion and exhaust occur. A split-cycle engine is really an air compressor on one side with a combustion chamber on the other.

Split-cycle engines appeared as early as 1914. Many different split-cycle configurations have since been developed; however, none has matched the efficiency or performance of conventional engines.



Previous split-cycle engines have had two major problems - poor breathing (volumetric efficiency) and low thermal efficiency.

Breathing (Volumetric Efficiency)

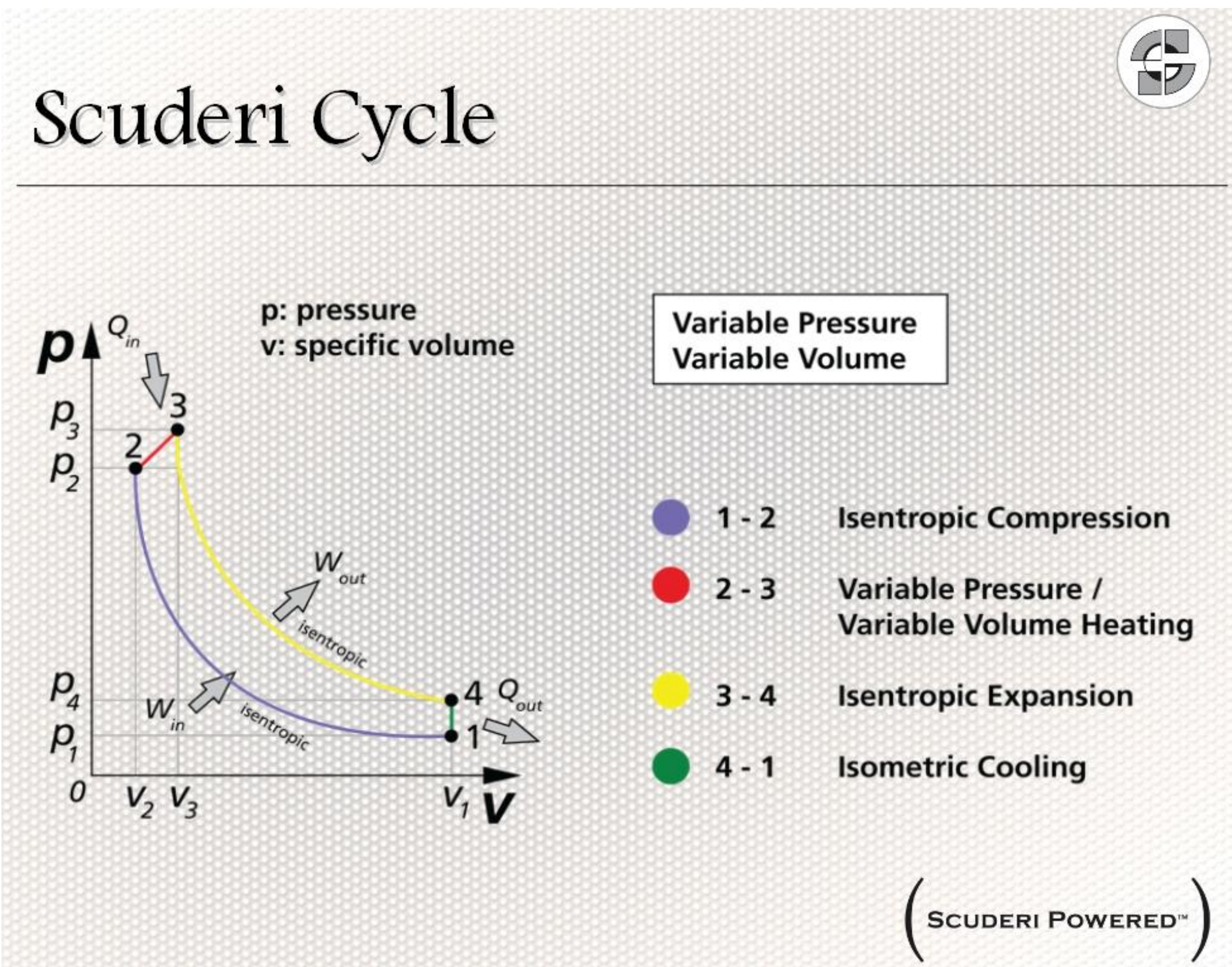
The breathing problem was caused by high-pressure gas trapped in the compression cylinder. This trapped high-pressure gas needed to re-expand before another charge of air could be drawn into the compression cylinder, effectively reducing the engine's capacity to pump air and resulting in poor volumetric efficiency.

Low Thermal Efficiency

The thermal efficiency of split-cycle engines has always been significantly worse than a conventional Otto cycle engine. The primary reason: They all tried to fire like a conventional engine - before top dead center (BTDC).

In order to fire BTDC in a split-cycle engine, the compressed air, trapped in the crossover passage, is allowed to expand into the power cylinder as the power piston is in its upward stroke. By releasing the pressure of the compressed air, the work done on the air in the compression cylinder is lost. The power piston then recompresses the air in order to fire BTDC.

By allowing the compressed gas in the transfer passage to expand into the power cylinder, the engine needs to perform the work of compression twice. In a conventional engine, the work of compression is done only once; consequently, it achieves much better thermal efficiency.



2.2] Why is the Scuderi Split-Cycle Engine Better?

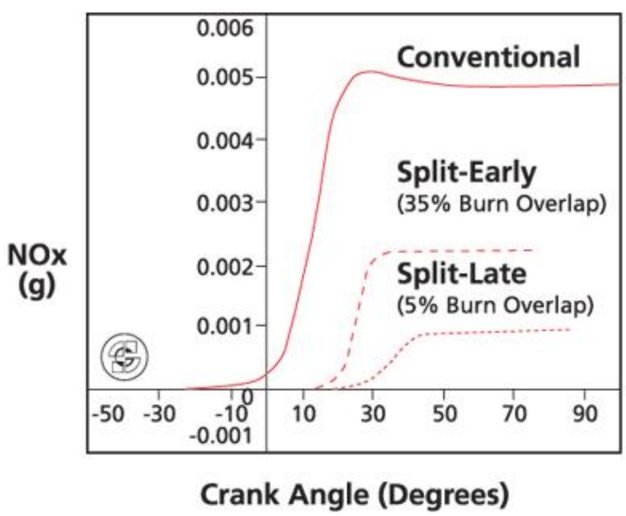
The Scuderi Split-Cycle Engine solves both the breathing and thermal efficiency problems with **two unique** and **patented concepts.**

➢ Unique Valve Design

On the compression side of the Scuderi Engine, the breathing problem is solved by reducing the clearance between the piston and the cylinder head to less than 1 mm. This design requires the use of outwardly opening valves that enable the piston to move very close to the cylinder head without the interference of the valves. This effectively pushes almost 100 percent of the compressed air from the compression cylinder into the crossover passage, eliminating the breathing problems associated with previous split-cycle engines.

➢ Solving the Thermal Efficiency Problem - Firing After Top Dead Center (ATDC)

Although considered bad practice in conventional engine design, firing ATDC in a split-cycle arrangement eliminates the losses created by recompressing the gas. The big issue was not how to solve the thermal efficiency problem of the split-cycle engine, but rather how to fire ATDC. In fact, **determining how to fire ATDC is possibly the single most important breakthrough of the Scuderi Engine design.**



2.3] P-V Curves

How does storing energy in the form of compressed air increase the efficiency of the system?

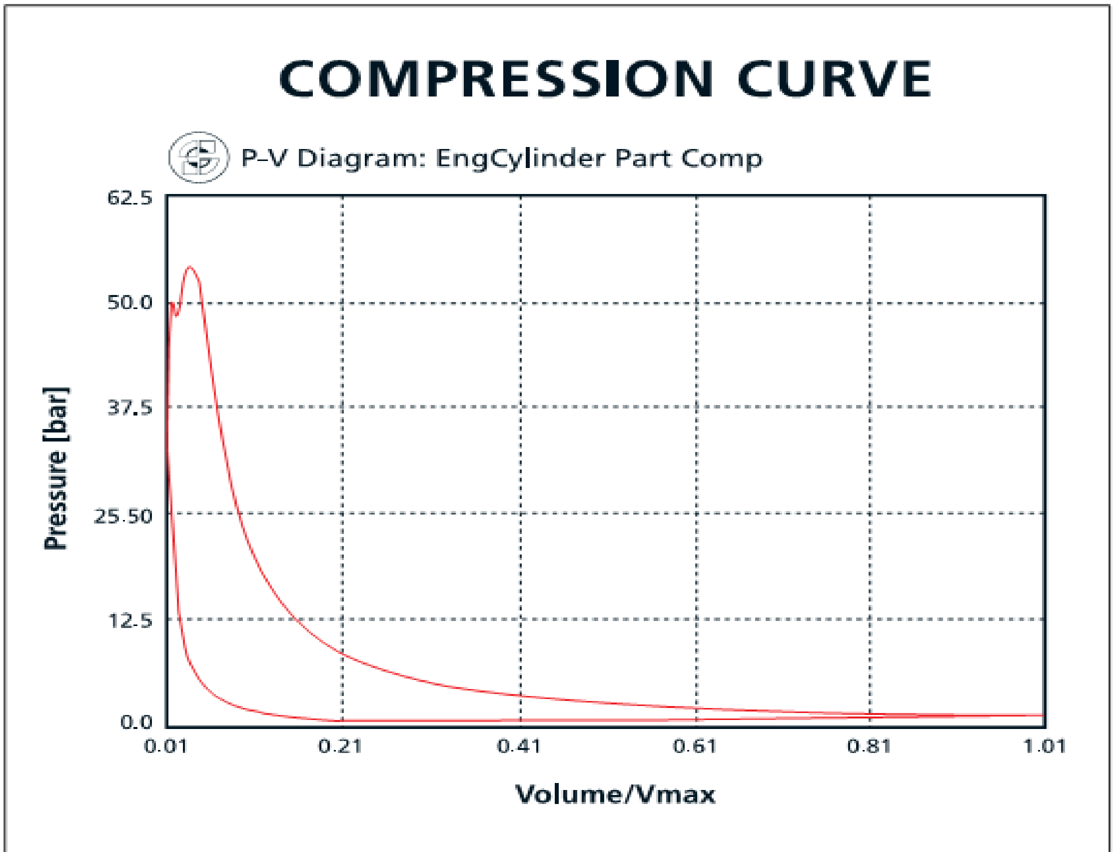
The answer is in the thermodynamics of the pressure and volume changes that are used by an engine to produce mechanical work.

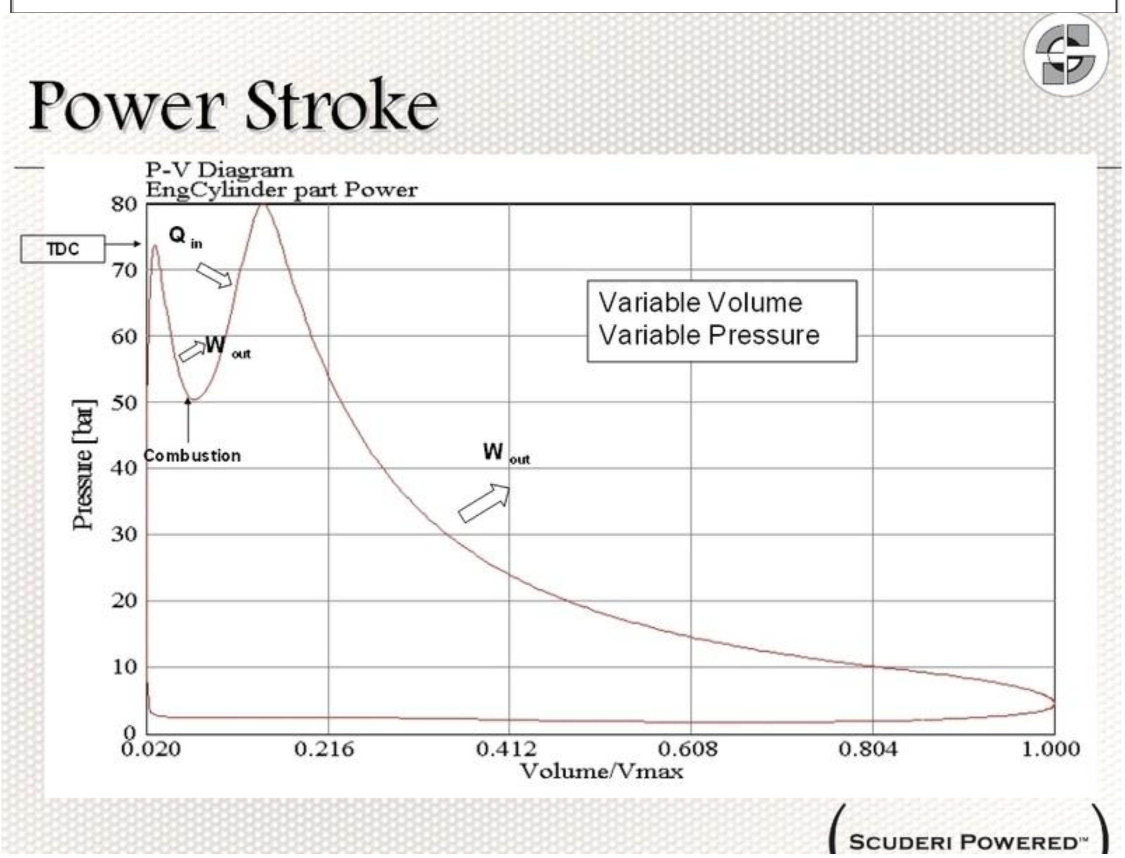
In an internal combustion engine, the two high-pressure strokes of compression and power consume and produce energy. The compression stroke is negative work, or energy that the engine expends to do work on the gas. The power stroke is positive work, or energy that the expanding gases of combustion perform on the engine to create mechanical work.

The net energy produced by the engine (its efficiency) is the energy generated during the power stroke less the amount of energy consumed by the compression stroke. The areas inside the curves reflect the amount of energy used or generated during each cycle.

The net energy produced by the Scuderi Split-Cycle Engine is the difference between the two pressure-volume curves.

Whenever the engine is operating on compressed air stored in its air storage tank, the losses due to compression are reduced to nearly zero. The resulting efficiency of the engine under this mode of operation is essentially the total area of the power curve.

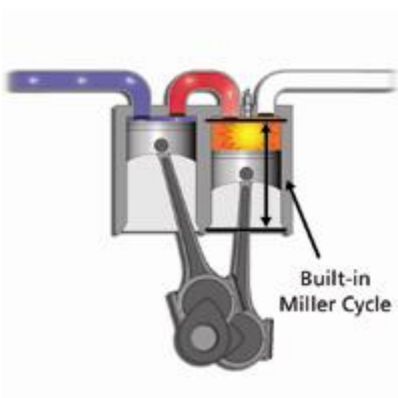

COMPRESSION CURVE
P-V Diagram: EngCylinder Part Comp
Pressure [bar]
62.5
50.0
37.5
25.50
12.5
0.0
0.01
0.21
0.41
0.61
0.81
1.01
Volume/Vmax


Power Stroke
P-V Diagram
EngCylinder part Power
TDC
Q in
W out
Combustion
W out
Variable Volume
Variable Pressure
Pressure [bar]
80
70
60
50
40
30
20
10
0
0.020
0.216
0.412
0.608
0.804
1.000
Volume/Vmax
SCUDERI POWERED™

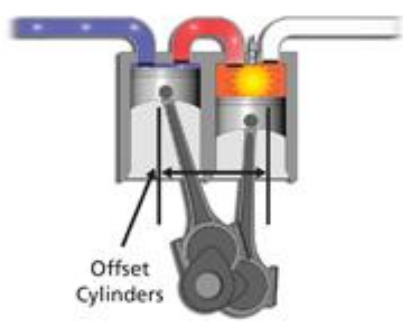
2.4] <u>The Revolution</u>

A Split-Cycle Engine Firing After Top Dead Center (ATDC)

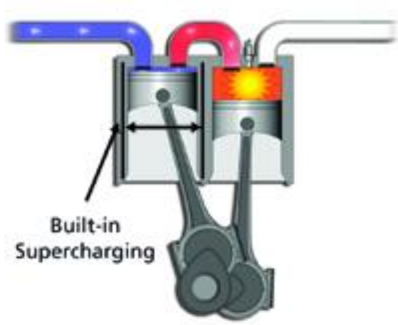
The revolutionary feature of the Scuderi Engine is the combination of a split-cycle design with the combustion process of firing ATDC. This combination is what produces a truly unique thermodynamic process that enables new levels to be reached for both efficiency and power. Its design is elegantly simple, leading to further enhancements that will continue to improve the



Built-in Miller Cycle



Offset Cylinders



Built-in Supercharging

The current NA prototype engine demonstrates the viability of the design. It proves that the concept of splitting the cycles and firing ATDC is real, and it is just the start of many design improvements to come.

Developments, Findings and Features of the NA Prototype

Intake and Exhaust Valves Used to Control Engine Load: The intake and exhaust valves are pneumatic valves that are fully variable in both lift and timing. The air needed to operate the valves is provided internally from the compression side of the engine. These valves are used in place of a throttling valve to control the engine during part-load operation.

Crossover Valves: The valves for the inlet and outlet of the crossover passage are cam actuated and are designed to lift outwardly. Air springs are utilized to return the crossover valves with the makeup air for the air springs being supplied internally from the compression side of the engine.

Crossover Passage: The crossover passage is a major control point for the engine. It is utilized for controlling pre-detonation (knock) by providing an additional cooling point after compression has occurred. This is a feature unique to the split-cycle design that is simply not possible in a conventional engine.

In addition, the configuration of the crossover passage going into the power cylinder has a significant effect on the air/fuel mixing, and the crossover passage design can also play a major role in controlling the engine at part load.

Fuel Delivery System: The Scuderi NA Engine utilizes Bosch injectors configured with a unique spray pattern. These injectors are a high-pressure, direct-injection type operating up to 200 bar. The combination of spray pattern, pressure and injection timing helps to ensure proper air/fuel mixing and prevent fuel from being trapped in the crossover passage.

Unique Power Piston Head Design: This engine utilizes a kidney-shaped depression in the piston head to enhance the air/fuel mixing. This unique design is part of the Company's patent portfolio.

Valve and Ignition Timing: One of the major factors required to obtain a good combustion process is combining valve performance with ignition timing. The Scuderi Engine utilizes a patented valve actuation mechanism that ensures high-velocity airflow into the power cylinder. Our combustion process of firing ATDC is then optimized by controlling the ignition timing of the engine.

Valve Lash Control: The combination of outwardly opening valves with low lift and rapid timing profiles requires a unique lash control device. Our team has developed a patented lash control mechanism specifically designed to accommodate the various operating conditions that the crossover valves will be under.

High Pressure and Massive Turbulence

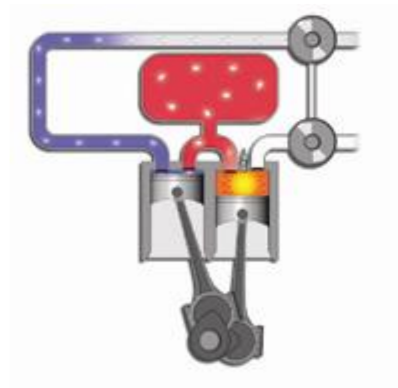
In the Scuderi Engine, firing ATDC is accomplished by using a combination of high-pressure air in the transfer passage and high turbulence in the power cylinder.

Because the cylinders in a Scuderi Split-Cycle Engine are independent from each other, the compression ratio in the compression cylinder is not limited by the combustion process. A compression ratio in the order of 75:1 is obtained, with pressure in the compression cylinder equal to that of a conventional engine during combustion. The pressure in the compression cylinder and the crossover passage reach more than 50 bar (725 psi) on our naturally aspirated (NA) engine and more than 130 bar (1885 psi) on our turbocharged (TC) engine.

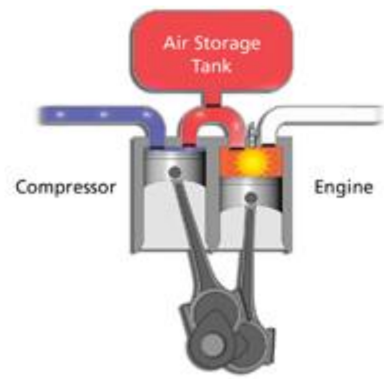
This high-pressure air entering the power cylinder creates massive turbulence. The turbulence is further enhanced by keeping the valves open as long as possible during combustion. The result is very rapid atomization of the air/fuel mixture, creating a fast flame speed or combustion rate faster than any previously obtained. The combination of high starting pressure and fast flame speed enables combustion to start between 11 and 15 degrees ATDC and end 23 degrees after ignition. **The result is a split-cycle engine with better efficiency and greater performance than a conventional engine.**

2.5] <u>The Evolution</u>

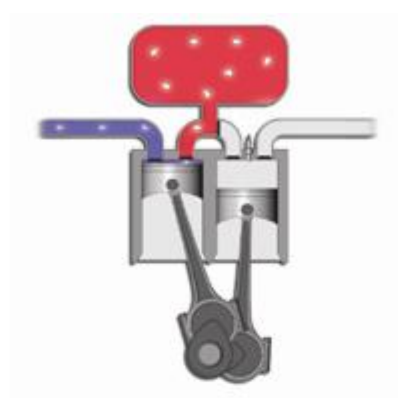
If the revolution is the Scuderi Split-Cycle Engine firing ATDC, then the evolution is the designs that flow from this unique engine concept.



Air-Hybrid Mode



Regenerative Braking

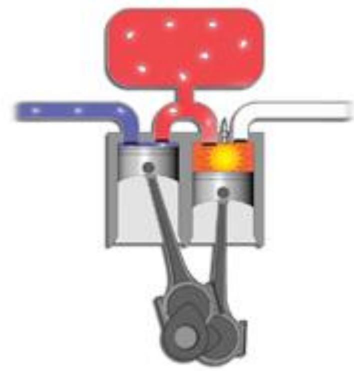


Turbocharged Split-Cycle Engine (High Torque, High Speed, Enormous Power, Smaller Engines)

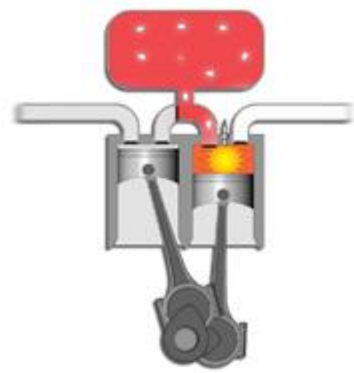
The next step in the development of the Scuderi Split-Cycle Engine is the turbocharged version. Because the crossover passage provides an opportunity to cool the intake air after it is compressed, the Scuderi Split-Cycle Engine has a very high resistance to pre-detonation (knock). This high resistance to knock potentially enables the Scuderi Split-Cycle Engine to boost or turbocharge to more than 2.5 bar absolute pressure. A conventional gasoline engine typically can boost to only 1.5 bar absolute before pre-detonation occurs.

The result is a significantly higher brake mean effective pressure (BMEP) and torque level. In fact, the torque level of the Scuderi Split-Cycle Engine matches or exceeds most turbocharged diesel engines. However, a Scuderi Split-Cycle Engine can potentially obtain rated speeds of up to 6000 rpm. The combination of diesel like torque levels matched with gasoline like speed levels would result in a power density higher than any conventional engine available today. **The Scuderi Split-Cycle Turbocharged Engine has a potential power rating at 6000 rpm of up to 101 kW per liter.**

Cruising Mode



High-Efficiency Mode



Turbocharged Mode

The Scuderi Engine enables the industry to drastically downsize its engines **(reducing fuel consumption and CO2 emissions)** without compromising performance.

Air-Hybrid Design

Because the Scuderi Engine is really a dedicated compressor on one side and an engine on the other, it simply requires the addition of an air storage tank and some controls to convert it into a hybrid system that can capture and store energy lost during the normal operation of the engine.

Since the turbocharged version of the Scuderi Engine operates at 130 bar, it will be able to store a significant amount of energy in its air tank. There are various engine control strategies that can be employed to improve the overall reduction in fuel consumption. This includes engine shutoff at idle, air-only driving, off-loading of the compression cylinder and regenerative braking.

The Scuderi Air-Hybrid provides a cost-effective hybrid solution that does not compromise performance.

Scuderi Split-Cycle Diesel Engine (Reduced Emissions)

One of the biggest benefits of the Scuderi Split-Cycle Engine for diesel applications is the reduction in emissions. The tougher emission standards that will begin in 2010 are causing the cost of diesel engines to dramatically increase while performance is being compromised.

The Scuderi Engine's combustion process of firing ATDC has an unusual effect of reducing both soot and NOx. This results from the combustion cylinder in the Scuderi Engine having a higher average temperature but at the same time a lower peak temperature than a conventional engine. The high average temperature, along with the high turbulence in the combustion process, is expected to reduce soot. However, lower peak temperatures resulting from combustion gases rapidly expanding when firing ATDC occurs, reduces NOx emissions by as much as 80 percent.

The Scuderi Split-Cycle Engine offers a unique opportunity to reduce emissions to the new levels without the need for costly after treatment systems.

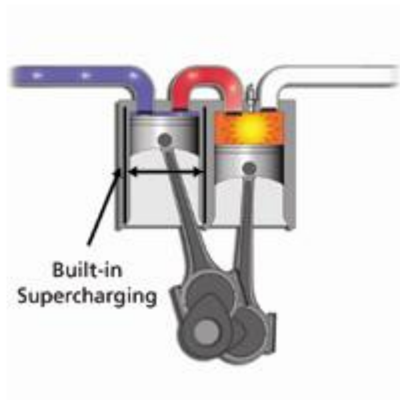
Promise of the Scuderi Split-Cycle Engine

With the revolution of the Scuderi Split-Cycle Engine firing ATDC and its evolution into the various configurations of naturally aspirated, turbocharged, air-hybrid and diesel designs, the Scuderi Split-Cycle Engine Technology provides a simple but elegant solution to meet today's - and tomorrow's - engine demands for increased efficiency, improved power, downsizing and lower emissions.

2.6] Advantages of the Scuderi Split-Cycle Design

A] One of the biggest advantages of the Scuderi Split-Cycle Technology is design flexibility. Many features that require additional equipment or are just too difficult to implement in a conventional engine design are easily accomplished with a Scuderi Split-Cycle configuration. For example, **supercharging** can be added simply by increasing the diameter of the compression cylinder.

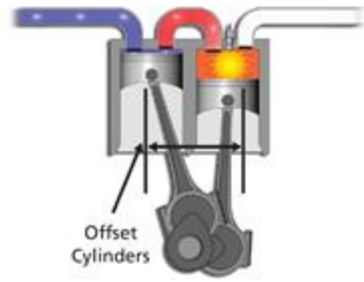
SUPERCHARGER



A supercharger is an air compressor used for forced induction of an internal combustion engine . The greater mass flow-rate provides more oxygen to support combustion than would be available in a naturally-aspirated engine, which allows more fuel to be provided and more work to be done per cycle, increasing the power output of the engine.

A supercharger can be powered mechanically by a belt, gear, shaft, or chain connected to the engine's crankshaft. It can also be powered by an exhaust gas turbine. Any turbine-driven supercharger is technically called a turbosupercharger, but more commonly called a turbocharger.

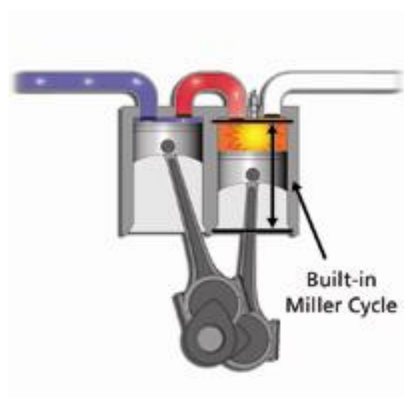
The term supercharger usually refers to any pump that forces air into an engine, but, in common usage, it specifically refers to pumps that are driven mechanically by the engine, as opposed to turbochargers which are always turbine-driven by the pressure of the exhaust gases.



B] **Piston friction can be reduced** by offsetting the compression and power cylinders.

C] A **Miller cycle** can be achieved simply by increasing the length of the power cylinder.

ABOUT THE MILLER CYCLE:



In the Miller cycle, the intake valve is left open longer than it would be in an Otto cycle engine. In effect, the compression stroke is two discrete cycles: the initial portion when the intake valve is open and final portion when the intake valve is closed. This two-stage intake stroke creates the so called "fifth" stroke that the Miller cycle introduces. As the piston initially moves upwards in what is traditionally the compression stroke, the charge is partially expelled back out the still-open intake valve. Typically this loss of charge air would result in a loss of power. However, in the Miller cycle, this is compensated for by the use of a supercharger. The supercharger typically will need to be of the positive displacement (Roots or Screw) type due to its ability to produce boost at relatively low engine speeds. Otherwise, low-rpm torque will suffer.

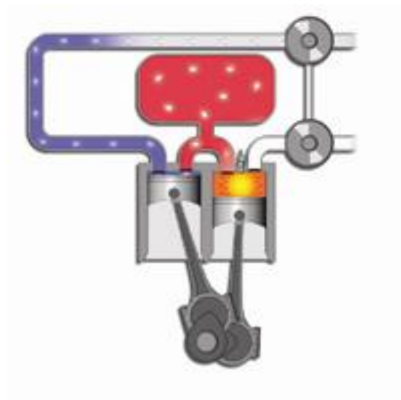
A key aspect of the Miller cycle is that the compression stroke actually starts only after the piston has pushed out this "extra" charge and the intake valve closes. This happens at around 20% to 30% into the compression stroke. In other words, the actual compression occurs in the latter 70% to 80% of the compression stroke.

In a typical spark ignition engine, the Miller cycle yields an additional benefit. The intake air is first compressed by the supercharger and then cooled by an intercooler. This lower intake charge temperature, combined with the lower compression of the intake stroke, yields a lower final charge temperature than would be obtained by simply increasing the compression of the piston. This allows ignition timing to be advanced beyond what is normally allowed before the onset of detonation, thus increasing the overall efficiency still further.

An additional advantage of the lower final charge temperature is that the emission of NOx in diesel engines is decreased, which is an important design parameter in large diesel engines on board ships and power plants.

Efficiency is increased by raising the compression ratio. In a typical gasoline engine, the compression ratio is limited due to self-ignition (detonation) of the compressed, and therefore hot, air/fuel mixture. Due to the reduced compression stroke of a Miller cycle engine, a higher overall cylinder pressure (supercharger pressure plus mechanical compression) is possible, and therefore a Miller cycle engine has better efficiency.

D - In the Scuderi Split-Cycle Engine, a **turbocharger** can be used to recover energy from the exhaust of the engine. Pressurized air from the turbocharger is fed into the compression cylinder, reducing the amount of energy needed for compression. The net energy gain provided by the turbocharged operating mode is unique to the Scuderi Split-Cycle Engine and cannot be achieved when using conventional engine technology.



TURBOCHARGER :

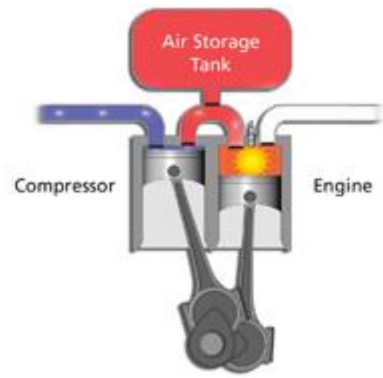
A turbocharger, or turbo, is a gas compressor that is used for forced-induction of an internal combustion engine. A form of supercharger, the turbocharger increases the density of air entering the engine to create more power. A turbocharger has the compressor powered by a turbine, driven by the engine's own exhaust gases, rather than direct mechanical drive as with many other superchargers.

A turbocharger is a small radial fan pump driven by the energy of the exhaust gases of an engine. A turbocharger consists of a turbine and a compressor on a shared shaft. The turbine converts exhaust heat and pressure to rotational force, which is in turn used to drive the compressor. The compressor draws in ambient air and pumps it in to the intake manifold at increased pressure, resulting in a greater mass of air entering the cylinders on each intake stroke.

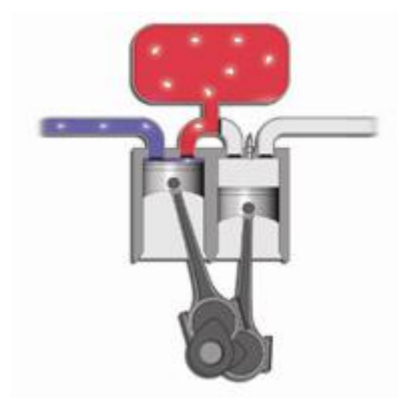
The objective of a turbocharger is the same as a supercharger; to improve the engine's volumetric efficiency by solving one of its cardinal limitations. A naturally aspirated automobile engine uses only the downward stroke of a piston to create an area of low pressure in order to draw air into the cylinder through the intake valves. Because the pressure in the atmosphere is no more than 1 atm (approximately 14.7 psi), there ultimately will be a limit to the pressure difference across the intake valves and thus the amount of airflow entering the combustion chamber. Because the turbocharger increases the pressure at the point where air is entering the cylinder, a greater mass of air (oxygen) will be forced in as the inlet manifold pressure increases. The additional air flow makes it possible to maintain the combustion chamber pressure and fuel/air load even at high engine revolution speeds, increasing the power and torque output of the engine.

Because the pressure in the cylinder must not go too high to avoid detonation and physical damage, the intake pressure must be controlled by venting excess gas. The control function is performed by a wastegate, which routes some of the exhaust flow away from the turbine. This regulates air pressure in the intake manifold.

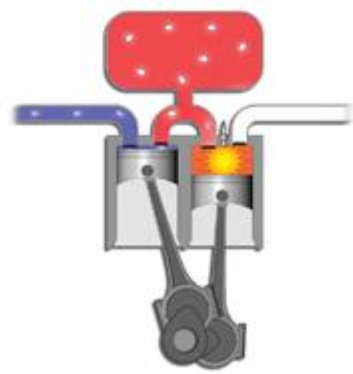
Scuderi Air-Hybrid Engine – The First Hybrid System That Makes Sense



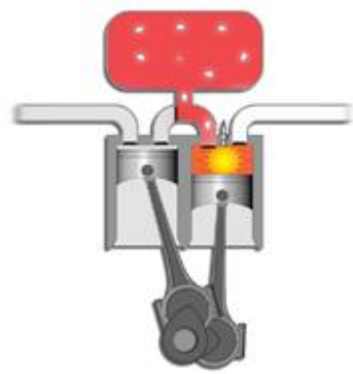
E] **Normal Operating Mode**: Because the Scuderi Split-Cycle Engine is a dedicated compressor on one side and an engine on the other, it only requires the addition of an air storage tank and related controls to convert it into a hybrid system that has the ability to capture and store the energy that is normally lost during operation of the engine.



F] **Regenerative Braking Mode**: By turning off the power cylinder while the vehicle is still engaged with the engine, and diverting the flow of compressed air to the air storage tank, the momentum of the vehicle continues turning the engine, thereby compressing air and storing it in the storage tank for later use.



G] **High-Efficiency Mode**: By turning off the compression cylinder and utilizing high-pressure air from the storage tank to supply the power cylinder, losses due to compression are reduced to nearly zero when operating in the high-efficiency mode.



H] **Cruising Mode**: High-efficiency cruising mode is achieved by sending only a portion of the compression cylinder's charge to the power cylinder. The remainder of the charge is sent to the air storage tank for later use. Whenever the air storage tank is full, the compression cylinder shuts off, and the vehicle operates in high-efficiency mode.

2.7] Gas Engines

Air-Hybrid Design

Because the Scuderi Engine is really a dedicated compressor on one side and an engine on the other, it simply requires the addition of an air storage tank and some controls to convert it into a hybrid system that can recapture and store energy lost during the normal operation of the engine.

Since the turbocharged version of the Split-Cycle engine operates at 130 bar, it will be able to store a significant amount of energy in its air tank. There are various driving strategies that can be employed to improve the overall reduction in fuel consumption. This includes engine shut off at idle, air-only driving, off-loading of the compression cylinder, and regenerative braking.

The Scuderi Air-Hybrid provides a cost effective hybrid solution that does not compromise performance.

Turbocharged Split-Cycle (High Torque, High Speed, Enormous Power, Smaller Engines)

The next step in the development of the Scuderi Split-Cycle engine is the turbocharged version. Because the crossover passage provides an opportunity to cool the intake air after it is compressed, the Scuderi Split-Cycle Engine has a very high resistance to pre-detonation (knock). This high resistance to knock enables the Scuderi Split-Cycle Engine to boost or turbo-charge to over 3 bar of pressure. A conventional gasoline engine typically can boost to only 1 to 1.5 bar before pre-detonation occurs.

The result is a significantly higher brake mean effective pressure BMEP and torque level. In fact, the torque level of the Scuderi Split-Cycle turbocharged gasoline engine matches or exceeds that of most turbocharged diesel engines. However at 6000 rpm, our rated speed is that of a typical gasoline engine. The combination of diesel-like torque levels, matched with gasoline-like speed levels, results in a power density higher than any conventional engine available today. The Scuderi Split-Cycle turbocharged engine has a power rating at 6000 rpm of over 145 hp per liter.

The Scuderi Engine enables the industry to drastically downsize its engines (reducing fuel consumption and CO2 emissions) without compromising performance.

2.8] Diesel Engines

Scuderi Split-Cycle Diesel Engine (Reduced Emissions)
One of the biggest benefits of the Scuderi Split-Cycle Engine for Diesel applications is the reduction in emissions. The tougher emission standards that will begin in 2010 are causing the cost of Diesel engines to dramatically increase while performance is being compromised.

The Scuderi Engine's combustion process of firing ATDC has an unusual effect of reducing both soot and NOx. This results from the combustion cylinder in the Scuderi Engine having a higher average temperature but at the same time a lower peak temperature than a conventional engine. The high average temperature, along with the high turbulence in the combustion process, is expected to reduce soot. However, lower peak temperatures, resulting from combustion gases rapidly expanding when firing ATDC occurs, reduces NOx emissions by as much as 85%.

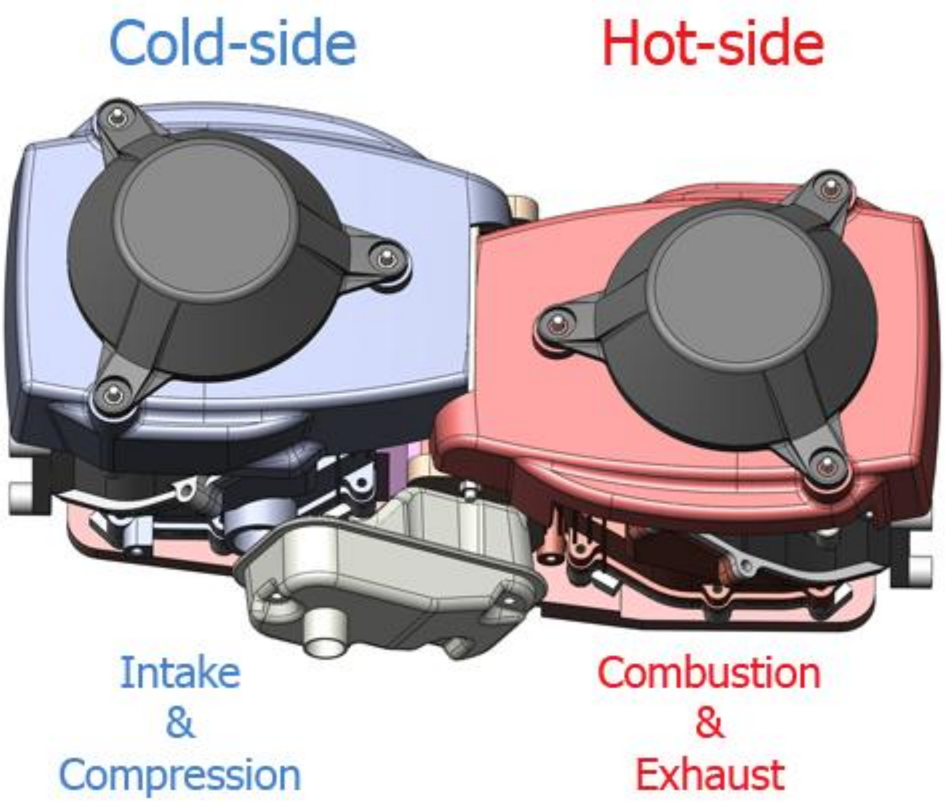
The Scuderi Split-Cycle Engine offers a unique opportunity to reduce emissions to the new levels without the need for costly after treatment systems.

3. TOUR ENGINE:

TourEngine™ is a patented opposed-cylinder split-cycle combustion engine with the potential for substantial efficiency gain as a result of its superior thermal management. It also offers significant reduction in noxious emissions. Notably, compared to hybrid and electric engine technologies that offer improved efficiency but are expensive and complex, TourEngine™ is simple as it is based solely on current cylinder/piston technology.

The TourEngine™ splits the conventional 4-stroke cycle between two opposing cylinders: a Cold-Cylinder that hosts the intake and compression strokes, and a Hot-Cylinder that hosts the combustion and exhaust strokes. Splitting the cycle allows flexibility in the design and thermal management, consequently leading to improved energy utilization. The direct coupling of the two cylinders, a fundamental deviation from previously proposed split-cycle designs, minimizes the potential losses from splitting the cycle.

Overall, TourEngine™ presents a cost-effective alternative with a substantial increase in engine efficiency and an opportunity to revolutionize the way combustion engines are built.



Standard gasoline engines utilize less than 30% of the fuel's potential energy, while over 70% of its energy is lost. This huge energy waste is also associated with high CO2 and NO'x noxious emissions. Much of this wasted energy and harmful emissions are due to compromises inherent to current 4-stroke internal combustion engines design, which hosts all four strokes in a single cylinder.

Over 70% of the fuel's energy is lost, most of it through the exhaust due to incomplete expansion and to the radiator cooling the engine

The **two major losses** are:

- **Exhaust Loss** (~27%) – The single cylinder size is a compromise between optimal expansion and compression sizes. As a result, the cylinder size is too small to allow complete expansion of the combusted charge, and therefore the exhausted gas contains unutilized heat energy.

- **Cooling Loss** (~37%) – A cooler environment is required for an efficient Intake and Compression. To provide these conditions the radiator continuously "steals" heat to cool the cylinder. However, overcooling during the combustion stroke is highly inefficient.

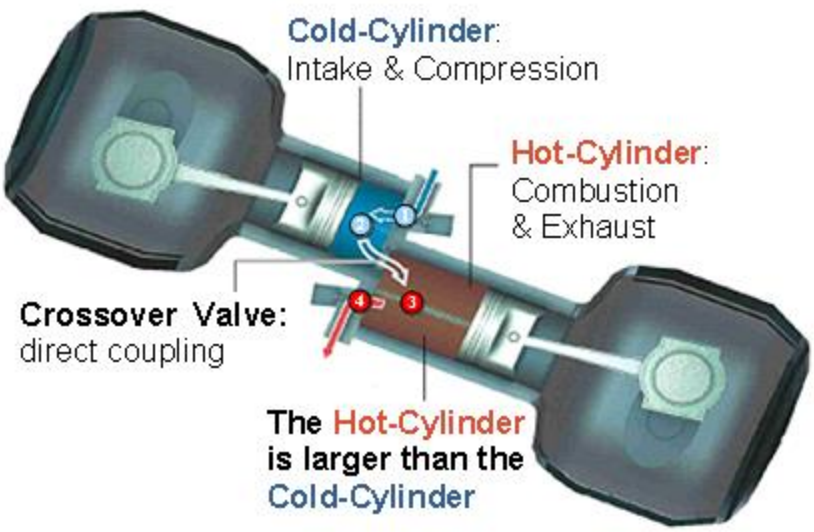
- Tour Engine Inc. patented a revolutionary inherently efficient design. Unlike current IC engines that use the same cylinder for all four strokes, TourEngine™ is designed to have two cylinders opposing each other that divide the traditional four stokes between them. This revolutionary design provides means to reduce the two big energy losses in common internal combustion engines - heat loss to the radiator coolant and exhaust thermal loss.

Two opposing cylinders
divide the traditional four
stokes between them

- In the TourEngine™ design the two cold strokes, Intake and Compression, occur in one relatively Cold-Cylinder, (left side in the figure) while the hot strokes, Combustion and Exhaust, occur in a different cylinder that is hotter and bigger (Hot-Cylinder, right side in the figure). In this configuration, the cold and hot strokes occur in parallel in the two cylinders.

The head-to-head configuration
permits direct connection,
ensuring efficient and complete
transfer of the compressed charge

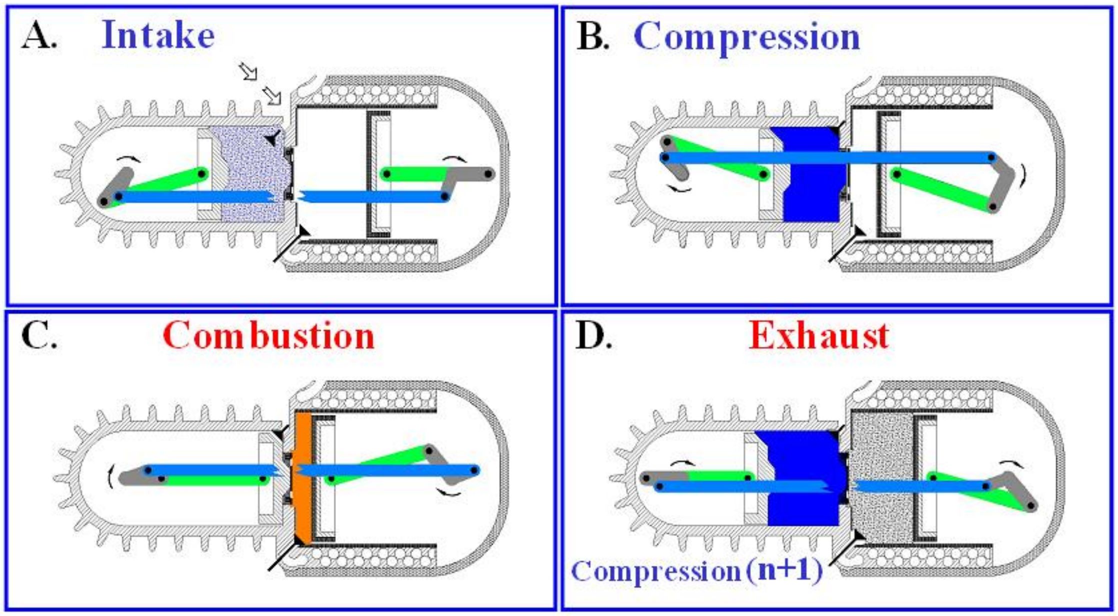
- A special crossover valve governs the precisely timed transfer of the compressed charge from the Cold-Cylinder to the Hot-Cylinder. The head-to-head configuration permits the direct coupling of the Cold and Hot cylinders and eliminates the need for a connecting tube. The absence of a connecting tube ensures minimal pressure loss and the dynamic and efficient transfer of the complete compressed charge between the Cold and Hot cylinders.



The figure above depicts a simplified cross-sectional view of the TourEngine™ cycle:

A. **Intake** – air and fuel enter the **Cold-Cylinder** through the open intake valve
B. **Compression** – after the intake is completed, the intake valve closes and the left piston compresses the working fluid within the **Cold-Cylinder**.
   Phase-lag – Notice that the **power-piston** (hot cylinder) is leading the **compression-piston** (cold cylinder) and has almost completed the exhaust stroke of the preceding cycle.
   Transfer – After the power-piston reaches its TDC (Top Dead Center), the exhaust valve closes and the crossover valve opens to permit the Transfer of the compressed working fluid from the Cold-Cylinder to the Hot-cylinder.
C. **Combustion** – Following closure of the crossover valve, the power stroke will progress in the Hot-Cylinder, while simultaneously in the Cold-Cylinder the next cycle will commence with the opening of the intake valve.
D. **Exhaust** – following the completion of the power stroke, the exhaust valve opens and the power-piston moves back to its TDC to completely clear the burned working fluid.

At any given time the TourEngine™ is simultaneously performing two consecutive cycles - as combustion occurs in the Hot-Cylinder, the intake of the next cycle starts in the Cold-Cylinder.



Notice that the two pistons of the **TourEngine™** do not have any "clearance" at TDC. The power-piston continues its movement all the way to the cylinder head, clearing away completely the burned working fluid. Only after the power-piston reaches its TDC, the exhaust valve closes and the crossover valve opens to permit the transfer of the compressed working fluid. The compression-piston also does not have a "clearance", therefore all the compressed working fluid is transferred to the combustion chamber, and then the crossover valve closes.

Increased efficiency

The TourEngine™ design permits reducing the two big energy losses that exist in current IC engines because it separates the location of the cold strokes from the hot strokes, thus enabling superior thermal management:

- **Less energy is lost to the radiator** – The **Cold-Cylinder** that hosts the Intake and Compression strokes remains cooler as the combustion stroke occurs only in the **Hot-Cylinder**. Consequently, less cooling is needed and therefore less energy is lost to the radiator.
- **Less energy is lost to the exhaust** – The **Hot-Cylinder** is designed to be larger than the **Cold-Cylinder** to maximize the conversion of heat/pressure energy to piston kinetic energy at the combustion stroke, as the combusted gas expands more fully.

Reduced emissions

The split-cycle design proves not only to be more efficient but also less polluting:

- **Up to 50% decrease in CO_2 emission**
- **Potential for a substantial decrease in NOx emissio**n
- **Reduction in CH and CO emission**

Additional advantages

Additional advantages of the TourEngine™ include higher torque, high-grade waste energy capture, complete combustion, efficient intake and efficient compression. These advantages and others are further described in internal documents (available upon request and NDA).