

Scuderi Split Cycle Research Engine: Overview, Architecture and Operation

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ABSTRACT

The Scuderi engine is a split cycle design that divides the four strokes of a conventional combustion cycle over two paired cylinders, one intake/compression cylinder and one power/exhaust cylinder, connected by a crossover port. This configuration provides potential benefits to the combustion process, as well as presenting some challenges. It also creates the possibility for pneumatic hybridization of the engine. This paper reviews the first Scuderi split cycle research engine, giving an overview of its architecture and operation. It describes how the splitting of gas compression and combustion into two separate cylinders has been simulated and how the results were used to drive the engine architecture together with the design of the main engine systems for air handling, fuel injection, mixing and ignition. A prototype engine was designed, manufactured, and installed in a test cell. The engine was heavily instrumented and initial performance results are presented.

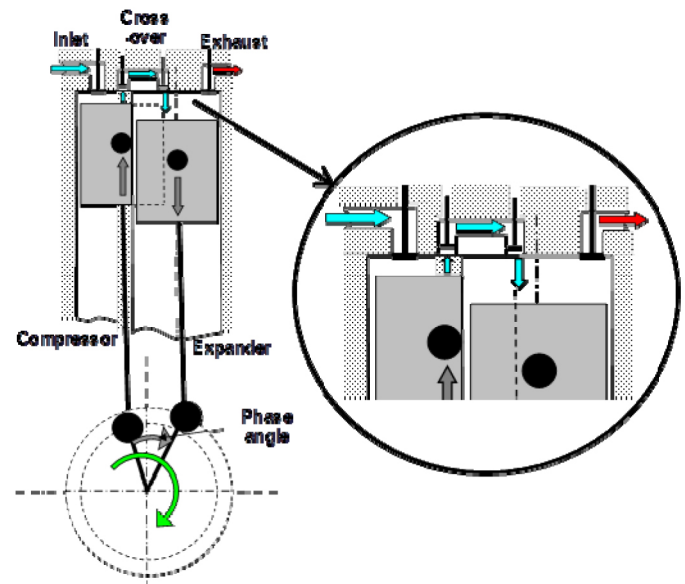


Figure 1. Principal Elements of Split Cycle Engine

INTRODUCTION

The Scuderi Split Cycle (SSC) engine concept was first conceived by Carmelo Scuderi, who filed the first patent for the concept on July 20, 2001 which was granted in 2003 [1]. This has been followed by supporting patents [2,3,4,5,6,7]. The SSC concept divides the four strokes of a conventional combustion engine cycle over two paired cylinders. The first cylinder, referred to as the “compressor”, provides intake and compression strokes. The second cylinder, referred to as the “expander”, provides power and exhaust strokes. The two cylinders are connected by a “crossover port” (Figure 1), through which the high pressure gas is transferred from the compressor cylinder to the expander cylinder between the compression and power strokes.

A major functional benefit of the SSC as an internal combustion engine is the separation of the compression and power (expansion) strokes which allows increased flexibility in optimizing these processes and designs. Other benefits of the SSC are the ability for substantial Miller/Atkinson cycle type operation (extended expansion during the power stroke compared to compression stroke), or pressure charging the expander with the compressor (cylinder supercharging), by use of differing compressor and expander displacements. Additionally, the crossover port arrangement enables charge motion, fuel and air mixing and combustion enhancement by means of the high pressure gas transfer from the crossover port to the expander. For SI applications, fuel injection can either be direct injection into the expander cylinder, or port injection into the crossover port during the gas transfer from

the compressor into the expander (or both). Either method of injection results in less time for fuel chemical reactions leading to pre-ignition (or knock) than with intake port fuel injection used on conventional SI engines.

Possible losses to be minimized in a split cycle engine are the flow pumping losses past the crossover valves and through the crossover ports, and energy losses due to heat transfer from the compressed air to the crossover port walls. Since the compressor cylinder has two cooler strokes, and the power cylinder has two hotter strokes, managing thermal loading is also a challenge for split cycle engines.

Due to the separation of strokes into compressor and expander cylinders, and fuel injection just ahead of or directly into the expander cylinder, the SSC engine concept adapts very well to pneumatic (air) hybrid operation, where compressed air can be transferred between the crossover passage(s) and a high pressure storage tank through a control valve or valves (Figure 2). A study is currently underway by SwRI to simulate this operation both with SSC engine simulation and also in a full vehicle simulation. Currently five major modes of operation have been included in the simulation:

- Normal Engine Firing (EF) - engine operating with normal firing and breathing (non-hybrid), with no air flow to or from storage tank
- Air Compressor (AC) - engine braking mode with expander cylinder disabled and compressed air flow from crossover port(s) to the storage tank during vehicle deceleration or downhill operation
- Air Expander (AE) - compressor cylinder disabled and compressed air flow from the storage tank to the crossover port(s) used to power the expander cylinder (no fuel injection or combustion)
- Firing and Charging (FC) - compressor cylinder produces more air flow than is needed to power the expander cylinder and vehicle, with excess air flow sent from crossover port(s) to storage tank
- Air Expander and Firing (AEF) - compressor cylinder disabled and compressed air flow from the storage tank to the crossover port(s) used to power the expander cylinder with fuel injection and combustion

Note that the FC and AEF modes are difficult to accomplish with a standard 4-stroke engine without negatively impacting efficiency. Further explanation of the air hybrid study and results will be presented in detail in a future paper at the completion of the study.

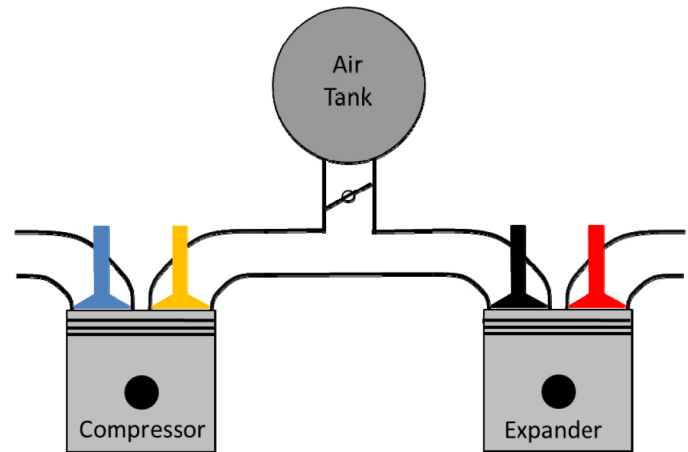


Figure 2. Air Hybrid Arrangement

While split cycle internal combustion engines can be traced to 1910 [8,9,10,11,12,13], the SSC is distinguished from previous designs by critical features including the phase angle between compressor and expander cylinders, the transfer of working fluid from the compressor to the expander substantially after top dead center (TDC) of the expander, post TDC combustion, and sonic flow from Xovr port to expansion cylinder over most of the speed-load range. As the combustion takes place in an expanding cylinder, the peak temperatures are significantly lower than in a conventional engine leading to greatly reduced NOx formation. All gas-exchange and thermodynamic events are repeated every engine revolution, i.e. over two strokes of each cylinder, such that the SSC can be viewed as a 4-stroke engine operating over two simultaneous 2-stroke cycles.

After initial conception of the SSC engine by Carmelo Scuderi, the Scuderi family continued the development and formed the Scuderi Group LLC. In 2002, Southwest Research Institute (SwRI) was contracted by the Scuderi Group and commenced work on the engine concept. Various phases were performed by SwRI, including:

- Initial Evaluation - completed July 2003
- Proof of Concept Study - completed July 2005
- Critical Issues Evaluation (Full Load) - completed July 2007
- Crossover Valve Train Test Rig - testing commenced in March 2008
- Prototype Research Spark Ignited Engine Design - commenced October 2007
- Prototype Research Spark Ignited Engine Testing - first firing June 2009

The results of these studies and developments are the SSC prototype research engine. The design was developed, similar to a single cylinder (conventional 4-stroke) research engine, as a flexible research tool to enable possible testing of both naturally aspirated (NA) and turbo-charged (TC) spark ignited (SI) concepts, as well as an eventual compression ignition (CI) diesel concept, with commonality of many engine structural features, dimensions and components. The following outlines the basic operation, major findings and future developments. Of particular interest for the initial engine testing are the unique engine breathing, fuel/air mixing, combustion and thermodynamic results compared to initial simulation predictions.

BASIC SSC ENGINE OPERATION

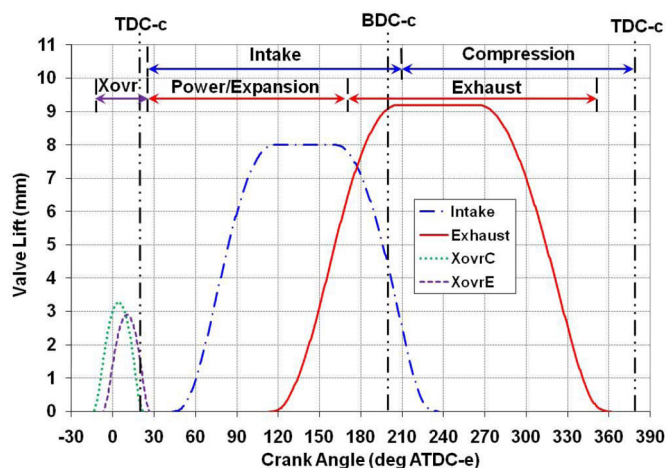


Figure 3. SSC main combustion events and valve lifts

Figure 3 shows typical valve events for the SSC SI NA engine at 4000 RPM, full load, from initial simulation optimizations. Note that the crank angle scale is referenced to degrees after TDC of the expander cylinder (ATDC-e). For the SSC prototype engine, the compressor TDC is phased 20° later than the expander TDC (TDC-e), and thus its crank angle scale is offset 20° later than the expander scale shown. The Scuderi cycle begins at intake valve opening (IVO) of the compressor. For this operating point intake valve closing (IVC) is after BDC of both cylinders. The intake and exhaust valves for the SSC prototype are pneumatically (air) actuated, allowing full variable valve actuation (VVA), so the IVC varies with speed and load, and thus early IVC is used in combination with the intake throttle to control engine mass air flow. Compression takes place from IVC until TDC of the compressor cylinder, and overlaps the openings of the valves at the ends of the crossover (Xovr) ports, both at the compressor end (XovrC valves) as well as at the expander end (XovrE valves). In addition to the 4 phases of the conventional 4-stroke cycle, the SSC Xovr port provides a modulated high pressure gas transfer phase from compressor to expander cylinders between and overlapping the

compression and power strokes. Prior to or slightly after XovrE valves open, fuel injection begins into the Xovr ports just ahead of the XovrE valves, and air and fuel mix enters the expander cylinder. As XovrE valves are nearly closed, spark ignition begins the power stroke. The power stroke ends when the exhaust valve opens (EVO) in the expander cylinder; the valve closes (EVC) just before TDC-e, ending the Scuderi cycle. Note that with fully variable intake and exhaust valve events, IVO, IVC, EVO and EVC timings vary with engine speed and load to optimize performance.

RESEARCH ENGINE HARDWARE

CYLINDERS AND VALVETRAIN

The initial light duty SI application SSC research engine design has the compressor and expander cylinder pair arranged in an in-line configuration, connected by the Xovr ports and valves. Future designs may take advantage of the separation of compressor and expander power strokes into different cylinders by offsetting cylinder axes relative to the crankshaft center (désaxé), as a way to reduce piston side loading and friction. The crankpins of the compressor and expander are relatively phased by the cylinder phase angle. The design of the pistons, connecting rods, crankshaft and bearings follow conventional engine design practices. The basic engine structure (Figure 4) is designed for up to 200 bar peak cylinder pressures to allow future conversion to simulate TC SI operation, as well as possible conversion to CI operation. The piston bore diameters are the same for commonality of parts, machining and packaging. Different configuration cylinder displacements can most easily be effected using different piston strokes, and thus variants can share most basic parts except crankshafts and connecting rods. In addition, wet cylinder liners are housed in a separate barrel section of the engine, so changes to cylinder bore can also be made if necessary. As in conventional single-cylinder research engines, the SSC research engine contains two primary counterbalance shafts in the block to offset the inertias of the two pistons which are phased closely together.

Though various types of valves may be considered for the gas exchange system of the SSC, poppet valves are currently used for expediency and reliability. The current SSC intake and exhaust valves (Figure 5) are conventional inward opening (i.e. towards the piston) poppet valves which follow traditional 4-stroke valve sizing for diameter and lift for gas flow and mechanical requirements. Pneumatically driven actuators [14, 15] are used on the research engine which provide full variability of lift, duration and timing. While this gives a very flexible system for development purposes, an objective of the overall program is to determine the degree of flexibility required of the VVA system. It currently seems likely that sufficient functionality, even for air hybrid operation, could be provided by a mechanical VVA system.

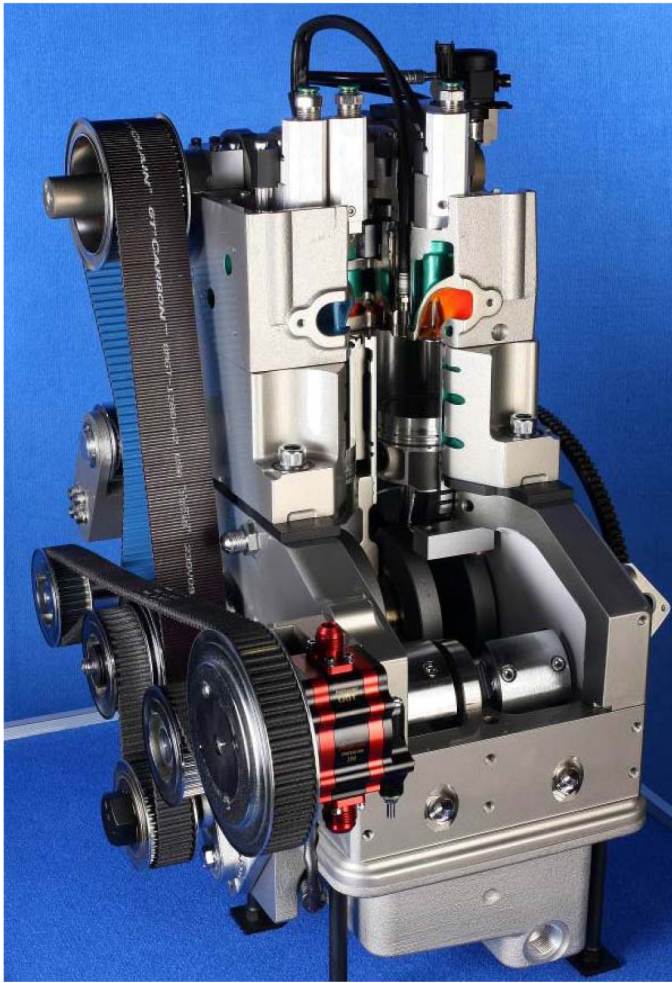


Figure 4. Cutaway Display Version of SSC Research Engine.

Both XovrC and XovrE valves are of the outward opening poppet type (away from the piston, Figures 5 and 6) in order to enable adequate opening around TDC without the limitation of piston interference or loss of compression ratio (CR) and expansion ratio (ER) due to accommodating clearance volumes in the cylinder head or piston. The Xovr valve diameters are 57% of the intake valve diameter (Table 1), reflecting the 10-15 kg/m³ density of the crossover gas at rated NA power levels. All valves are vertical, again with deference to manufacturing attainment of the 50:1 ER and 96:1CR values.

The Xovr valve lifts are approximately 35-40% of the intake valve lift (Figure 3) due to the short Xovr periods of 30-35° crank angle. The combination of valve opening period, engine rated speed and valve peak lift generate valve acceleration values similar to those of Formula One engines. A mechanical system was selected for the Xovr valvetrain using components highly optimized for inertia and stiffness, pneumatic valve springs and large diameter camshaft to control profile concavity. More extensive descriptions of the

unique Xovr valve train system, its development, testing and functional performance are given in [Reference 16](#).

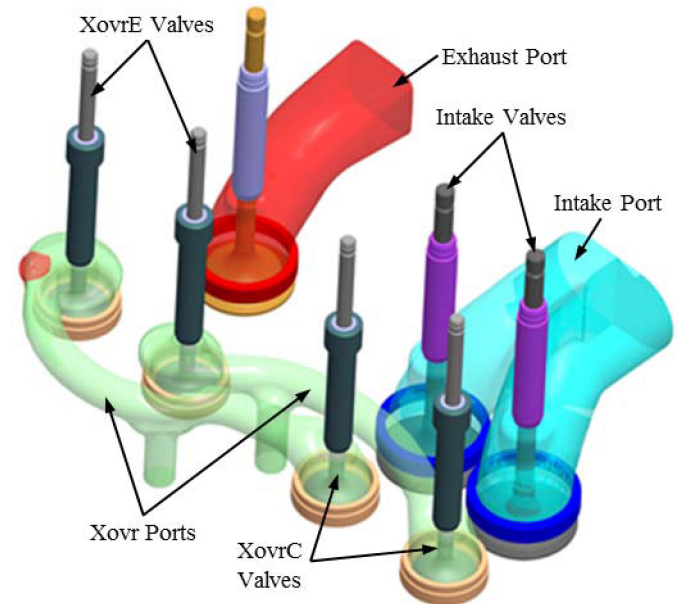


Figure 5. SSC Valve and Port Arrangement

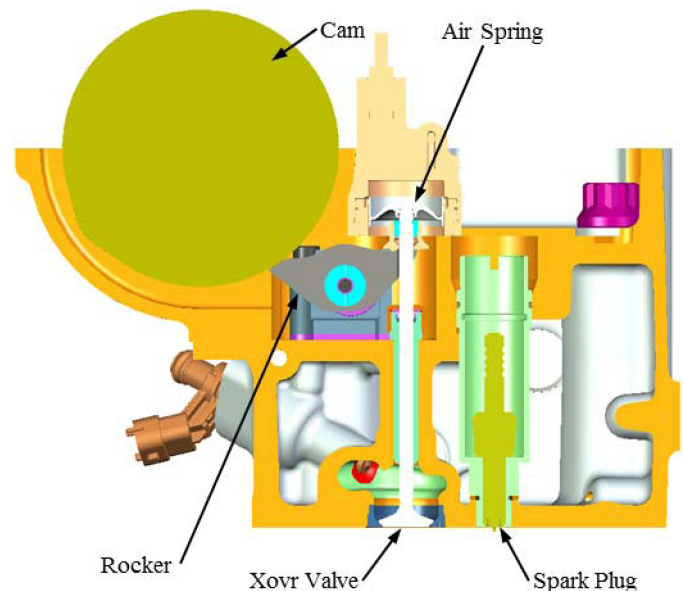


Figure 6. Crossover valve actuation arrangement and spark plug

PORTS, FUEL INJECTORS AND COMBUSTION SYSTEM

High flowing/neutral charge motion ports are used for the intake ports to the compressor while the exhaust port of the expander follows normal 4-stroke design practice. The compressor discharge entrance to the Xovr port (XovrC) also

aims for maximum flow and minimal charge motion, but the Xovr port exits to the expander cylinder (XovrE) must encompass port injection fuel preparation, targeting and charge motion generation. The fuel preparation and charge motion occur simultaneously and have to be completed in about 1-1.5 milliseconds at 4000 RPM, i.e. 25-35° crank angle.

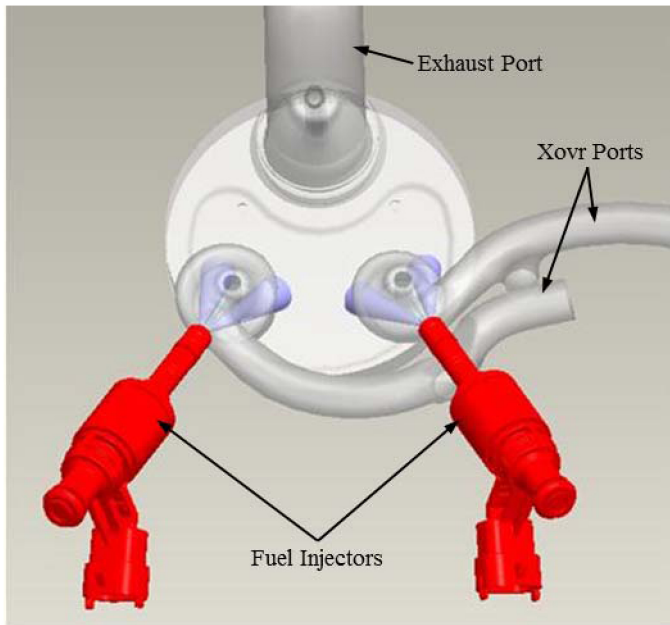


Figure 7. View showing Xovr port exits, exhaust port, Xovr port injectors and expander cylinder combustion bowl

The current SSC research design (Figure 7) uses two Xovr ports whose XovrE exits both have helical forms. The fuel injector in each port are designed for direct cylinder injection and thus can operate in the high temperature, high pressure Xovr port environment. They are capable of up to 200 bar injection pressure and currently have two spray targets for each injector, with a total of seven spray holes aimed at the two targets. The figure shows the spray plume targetings, which are aimed approximately at the Xovr valve/port openings. The rounded crescent shape of the shallow combustion bowl in the top of the expander piston was developed using three dimensional computational fluid dynamics (3D CFD) simulations to produce even distribution of the air-fuel mixture across the cylinder and to the two spark plug locations (not shown) at the tips of the crescent, while inhibiting initial pressure wave fuel distribution over the exhaust valve to suppress pre-ignition.

Figures 8 and 9 show views of the complete cylinder head assembly.

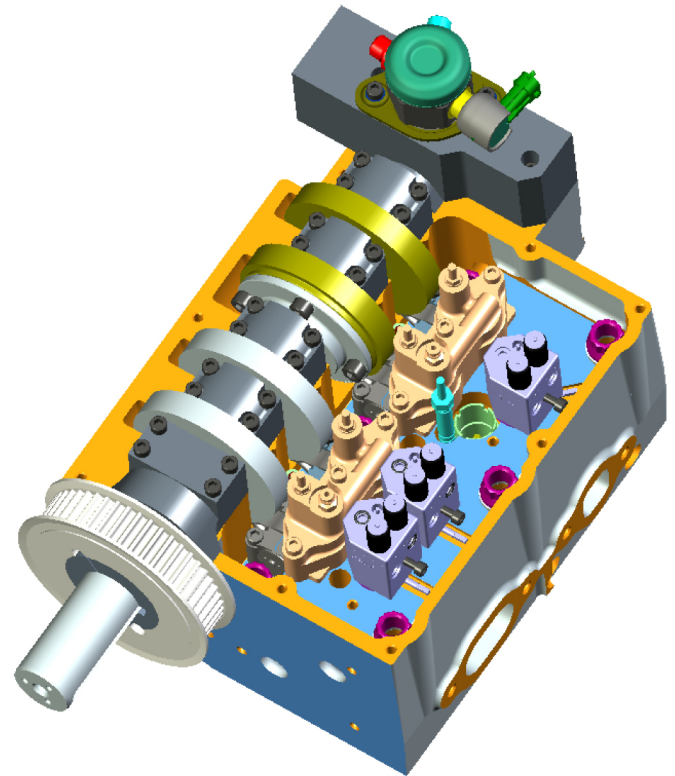


Figure 8. View of cylinder head assembly showing top, front and manifold faces

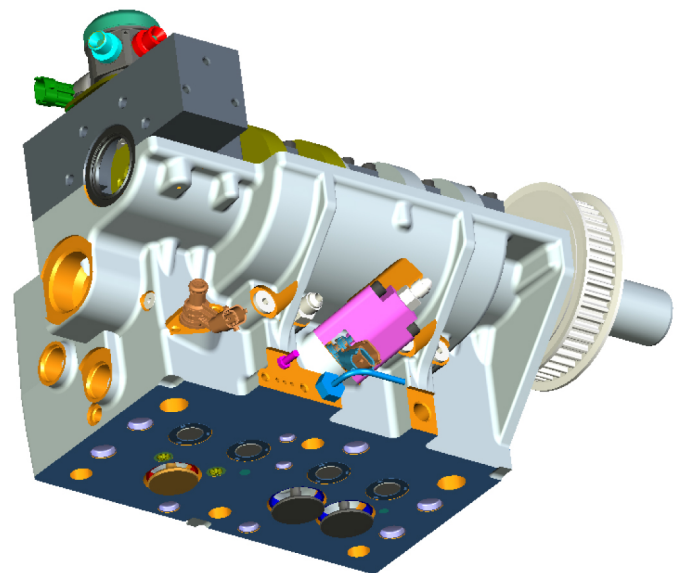


Figure 9. View of cylinder head assembly showing underside, fuel injectors and rear faces

SSC ANALYSIS AND OPTIMIZATION

SSC OPTIMIZATION PARAMETERS

The initial target for the SSC engine was for an NA light duty application and the combined displacement of the compressor and expander cylinder pair was set to 1.11L. The SSC use of discrete cylinders with variably-actuated valves for intake and exhaust introduces a large degree of flexibility for controlling the 4-stroke cycle. The key additional variables and features of the SSC, versus the 4-stroke cycle, are:

- Displacement ratios of the compressor and expander cylinders
- Bore/stroke ratios for compressor and expander; these can be different
- Compression and expansion cycle phasing (phase angle)
- Gas transfer phasing from the compressor to the expander (phase angle and crossover valve timing effects)
- Compressor CR and Expander ER values
- Xovr port volume and its effect on the effective CR and ER values.

A strategy for optimizing these variables was adopted which involved parallel paths of combustion 3D CFD and one dimensional (1D) engine performance simulation. The performance simulation was used to set the initial conditions for the CFD analysis, the results of which, particularly in terms of burn time and mass flow rates, were fed back into the performance simulation model so that both models became progressively more refined. At the same time, design studies were being carried out to ensure that practical arrangements of geometric features were being assumed by the simulations and in this way, it was possible to progress to the design of the research engine with the minimum of changes. The use of these performance analysis tools is described in more detail in the following sections.

1D PERFORMANCE PREDICTION

A 1D thermodynamic engine performance simulation [17] model was built for the SSC engine. This was initially exercised to run coarse sensitivity analyses to develop a preliminary specification for the engine. Output from this preliminary model was used to provide input data for the combustion CFD studies which are described later. The CFD results were then utilized to provide combustion rate information to the 1D modeling and to make adjustments so that the predicted mass flows correlated between the two methods.

Once a sufficient level of correlation had been achieved, a more detailed parametric study of the engine parameters was

carried out and the specification for the NA research engine was developed, [Table 1](#).

Table 1. SSC NA Gasoline Research Engine Specification

Compressor Bore	87 mm
Compressor Stroke	99 mm (81 mm TC)
Compressor Displacement	0.59 L (0.48 L TC)
Compression Ratio (geometric)	96:1
Expander Bore	87 mm
Expander Stroke	87 mm
Expander Displacement	0.52 L
Expansion Ratio (geometric)	50:1
Compressor/Expander Phase Angle	20°
Total Engine Displacement	1.11 L (1.0 L TC)
Intake Valves	2 x 35.1mm OD, inward opening
Exhaust Valve	1 x 33.1mm OD, inward opening
Crossover Valves	4 x 20.0mm OD, outward opening
Spark Plugs	2x

[Figure 10](#) shows a typical plot of predicted pressures vs. crank angle and demonstrates some of the important features of the SSC engine. Firstly, with the exception of the area immediately adjacent to TDC-e, it can be seen that the pressure in the Xovr ports (black and green lines) remains essentially constant throughout the cycle. There are some oscillations predicted due to wave action and also a progressive loss in pressure of about 5 bar over the cycle which is due to heat loss from the ports.¹ As the XovrC valves open, the pressure in that part of the Xovr ports initially falls, indicating a small amount of backflow but this is only momentary. The XovrE valves open only shortly after the exhaust valve has closed (not shown on the diagram), and so the pressure in the expander cylinder does not rise significantly prior to this. From this point the compressor, the Xovr ports and the expander effectively form a single volume as all Xovr valves are open. It can be seen that the pressure in the compressor is transferred, with some phase lag, through to the expander where it peaks at around 10° ATDC-e. From this point, the pressure falls due to the downward motion of the expander piston until the effect of combustion takes over and causes a second peak later in the expansion stroke. Closure of the XovrE valve is timed to prevent the passage of combustion flame or pressure wave back into the Xovr ports.

¹No special measures are currently taken on the engine to insulate the Xovr ports as a way to improve overall efficiency but this remains an option for future development. Of potentially more interest may be the possibility to intensively cool the Xovr ports, particularly at high ratings (e.g. for a TC version), where the additional ‘aftercooling’ could prove to be very effective as a means of suppressing knock.