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SCAI COMBUSTION PROCESS
FOR DIRECT INJECTED ENGINES

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Sonex Research, Inc., (Sonex) a small business located in Annapolis, Maryland, was co-founded in 1980 by Dr. Andrew A. Pouring, a former Professor of Aerospace Engineering and Chairman of the Department of Aerospace Engineering at the U.S. Naval Academy. At Sonex, Dr. Pouring has conducted basic research into the principles of in-cylinder control of ignition and combustion. The Company's patented Sonex Combustion System (SCS) technology as it applies to four-stroke direct injected (DI) engines features chemical/turbulent enhancement of combustion for the reduction of emissions and the enablement of a new combustion process for normally aspirated and turbo-boosted or supercharged conditions. The SCS has also been applied to two-stroke spark ignited (SI) engines.

Sonex U.S. Patents No. 5,862,788 (January 1999), No. 6,178,942 B1 (January 2001) and others, address a combustion chamber for non-spark ignition, DI engines that improves the process of combustion through a combination of chemical and fluid dynamic effects as enabled by patented piston technology. The Company believes its SCS accomplishments have the potential to cause a four-stroke paradigm shift on engines designs for military and commercial/civil markets. Both markets are driven by needs for improved fuel economy, lower exhaust emissions, higher performance at the lowest cost and lowest size/weight possible.

The SCS for DI engines, based on patented piston technology containing micro-chambers (MC) with connecting vents as shown schematically in Figure 1, is applicable in *two distinctive paths*. The first path, the *Low Soot Diesel Design (LSDD),* enables soot and oxides of nitrogen (NO_x) reductions in standard DI diesel engines at compression ratios greater than 16:1. The second design path, called *Sonex Controlled Auto Ignition (SCAI),* is for low to moderate compression ratio (<12.5:1) DI engines and enables precise control of auto-ignition and combustion with single phase high rates of heat release for a variety of fuels. SCAI "sparkless" combustion in un-throttled, DI lightweight engines reduces emissions and significantly improves fuel economy due to the absence of a single flame front.

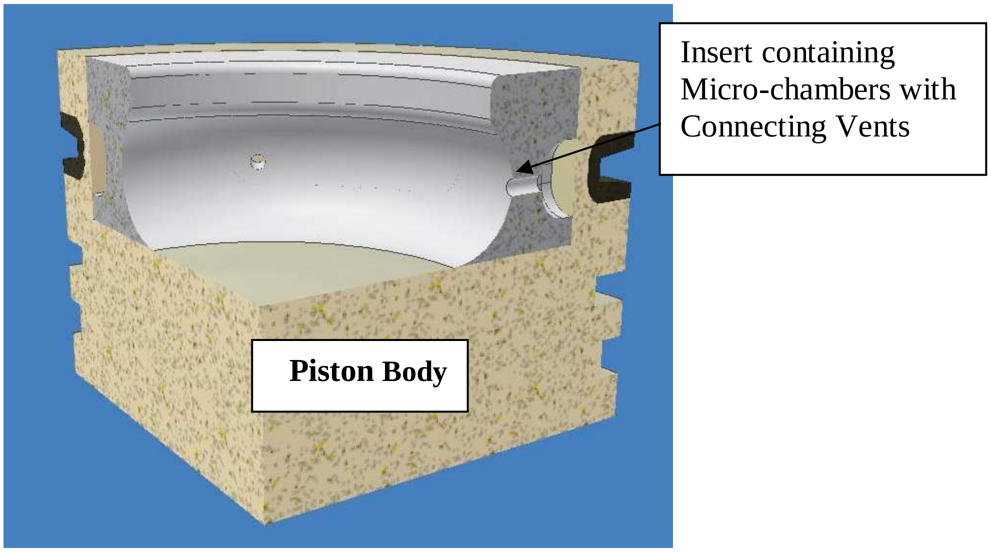

Figure 1
Cross Section of SCAI Piston for DI Engines

It should be noted that the *SCS for small two-stroke SI engines* that operate on kerosene-based "heavy fuels" is a derivative of these designs but *is not piston based;* SCS two-stroke heavy fuel engines have micro-chambers in the cylinder head according to U.S. Patent No. 5,855,192. This technology is licensed to Insitu, Inc. of Bingen, Washington, under an exclusive agreement for UAV applications of 20 horsepower of less and is in use in the ScanEagle UAV.

The SCAI Approach

This overview addresses the SCAI process that offers a paradigm shift in the design of reciprocating IC engines which up to now have been based on two basic ignition types: *spark-ignited (SI) gasoline* engines and *compression-ignited (CI) diesel* engines. However, a third definitive type of IC engine ignition has been under serious, and lately, intensive investigation. Called by various names, such as radical ignition (RI), activated radical combustion (ARC), homogeneous charge CI, (HCCI), etc., this third engine ignition type differs from the first two because it depends on *control of the chemical kinetics* of the ignition process. Though these various names may imply important differences in the details of these individual combustion approaches, there are commonalties that enable them all to be considered collectively under this third type of engine *ignition*. Instead of involving a progression of the combustion process (a flame) through the charge, this third approach involves the *simultaneous envelopment* of most of (or at least much more of) the charge. This approach, referred to as *homogeneous combustion* (or as *chemical kinetics controlled ignition*), will, if it can be controlled, improve the stability and uniformity (and thus also the repeatability from cycle to cycle) of the burn. Significantly, the Sonex form of the process makes feasible <u>*fully controllable*</u> lean burn, low emission auto-ignition over the full range of engine speeds and loads on low cetane fuels such as JP5/8, methanol, ethanol and *gasoline* at compression ratios (<12.5:1) that are much lower than normally required for fuels with such poor CI ignitability.

The SCAI process was developed from experience with SCS pistons for SI engines that originally possessed both acoustically tunable features as well as controllable auto-ignition features. The early design of the MC used in SI engines had an exterior chamber between the crown of the piston and the cylinder wall. The current SCAI design evolved by emphasizing the controllable auto-ignition process in the design of pistons for DI engines. A unique feature of the MC in the SCAI DI piston is its function for enabling the auto-ignition phase of the SCAI combustion process. The SCAI MC for DI engines evolved into a set of internal chambers positioned radially around the combustion bowl of the piston. The SCAI for DI features pistons containing strategically located MCs with connecting vents, having one MC per injector spray. Figure 1 above shows a cross section of the upper section of half of the SCAI piston used in DI engines.

Fundamentals of the SCAI process are supported by test data and peer reviewed theoretical papers on Chemical kinetics models published by the Society of Automotive Engineers (SAE). For example, SAE 2004-01-1677 for ignition of methane fuel clearly illustrates when and how radical chemical species and intermediates form and influence ignition when MCs are present. Conversely, *without the presence MCs,* when the compression ratio was increased to 18.8:1 (from the 15.5:1 value used to cause ignition of methane using MCs), kinetic calculations showed ignition *would not occur*.

The SCAI Combustion Process

To illustrate the four-stroke SCAI combustion process, we begin with the compression stroke as calculated in several SAE papers. Air flows into the MC at high velocity and contributes to cleaning the vent passage; Figure 2 is a graphic illustration of airflow into the MC during the compression stroke. As the piston approaches the end of the compression stroke, one or more precisely timed fuel injections take place prior to Top Dead Center (TDC) or the uppermost piston travel; the reentrant feature of the piston shape maximizes turbulence and thereby combustion bowl air/fuel mixing (homogenization).

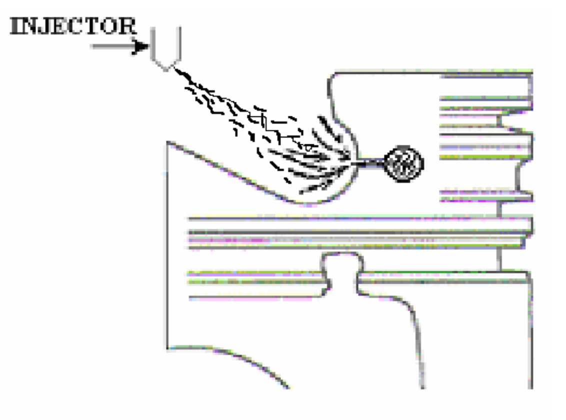

Figure 2
Compression Stroke

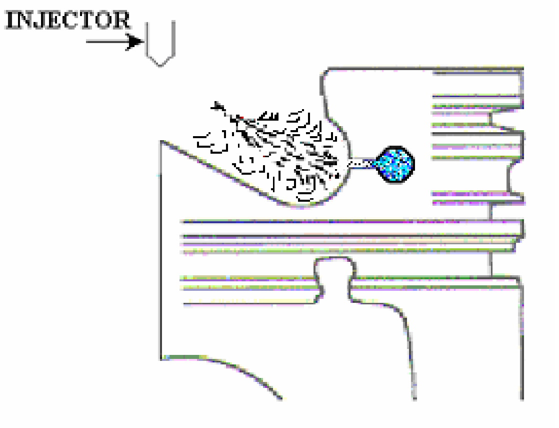

Figure 3
Fuel-Air Mixing, Ignition on Power Stroke

Figure 3 illustrates completion of fuel injection, homogenization of fuel in the bowl and the creation of the chemical radicals/intermediates in the micro-chamber after start of the power stroke. Because of strategic MC location and carefully timed injection, some fuel enters the MC and partial oxidation occurs within, creating highly reactive gasses (known as chemical radicals and intermediate species). During the *initial* piston movement on the power stroke (ATDC), rapid cylinder gas expansion prior to combustion briefly causes a pressure difference between the MC and combustion bowl due to the constricted connection vent. The higher pressure in the MC expels the partially reacted gases or active chemical species in advance of the leading edge of the combustion front in the combustion bowl. Flow reversal due to increasing cylinder pressure then causes MC inflow; the vents quench any flame propagation into the MC. Temperatures remain below the auto-ignition point in the MC preserving a portion of the reactive gasses for later in the cycle.

As the power stroke reaches 8 to 12 degrees after TDC, simultaneous inflammation of the entire mixture is initiated in the combustion bowl, enabled by distributed active chemical species in the combustion bowl, rapidly raising the cylinder pressure. The combustion event occurs at a high rate over ~17 crank angle degrees (CAD). A pressure differential is again created between the MC and the combustion gases, forcing and quenching some combustion products into the MC which further promote reactions within the MC.

Towards the end of the power stroke the cylinder pressure and temperature fall faster than in the restricted MC and the reactions within the MC “freeze” (reactions cease) due to the decreasing temperatures. However, the pressure differential causes high velocity jets to flow out of the MCs causing turbulence and combusting a high percentage of any particulates formed in the piston bowl. During MC evacuation a velocity of 500 ft/sec was calculated earlier in a *motored* engine where, of course, no reactions were possible.

Figure 4 illustrates the high velocity jet from the MC, causing turbulence and promoting reaction in the combustion bowl; the MC must be properly sized according to cylinder displacement. During the exhaust stroke the cylinder pressure begins to rise causing another flow reversal into the MCs, again forcing partially spent and unspent gases back into the MC. When the next *intake stroke* starts, the pressure inside the cylinder drops below *the previous cylinder pressure during the exhaust stroke*. This allows the remaining partially oxidized “frozen” reactants to exit from the MC and seed or fumigate the intake air with “frozen” chemical species that are reactivated when heated by the temperature increase of compression to enable ignition of low cetane fuels at a 12.5:1 compression ratio. Figure 5 illustrates fumigation of the intake charge early in the intake stroke.

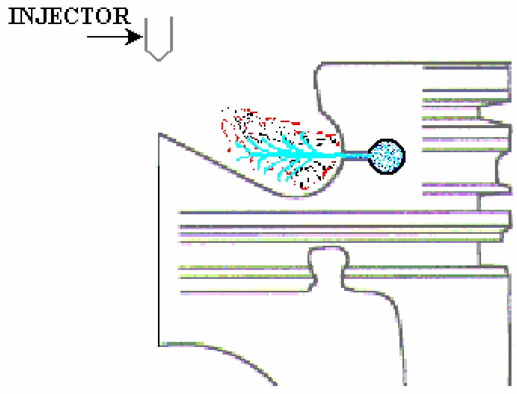

Figure 4
End of Power Stroke

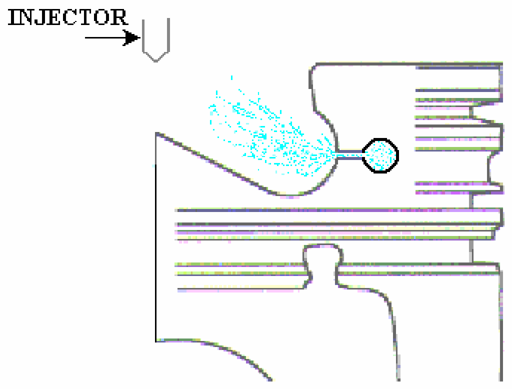

Figure 5
Intake Stroke

Auto-ignition of the main charge is enabled at temperatures calculated to be 100^{o}-200^{o}C below those normally required for compression ignition. Because of the high mixing levels, this radical initiated auto-ignition takes place simultaneously *at many sites throughout the combustion chamber*. The *elimination of a flame front* enables simultaneous envelopment of most of the fuel/air charge in the cylinder, resulting in a more rapid and more complete lean burn at lower peak temperatures, thereby achieving a reduction in soot, CO, CO_2 and nitrogen oxide formation (NO_x). It is, in part, because of the possibility of operating the engine at lower compression ratios (due to the presence of ignition enabling radicals in the main chamber) that emissions are greatly reduced.

The SCAI design path has the potential to provide a paradigm shift in combustion technology. This no-spark, quasi-homogeneous combustion process demonstrates *fully controllable* low compression auto-ignition by using *properly timed injection from idle to full load.* The chemical species seeded into the un-throttled air on the intake stroke together with timed direct injection enable low compression ratio auto-ignition and homogeneous (or nearly so) combustion. Homogeneous combustion is evidenced by *single-phase* high rate of combustion occurring *after completion of fuel injection* at all speeds and loads yielding low $NO_{x,}$ soot and other climate changing emissions. An added benefit of the very short time heat release is a significant reduction in heat losses to further improve fuel economy.

Application of the SCAI

Recently Sonex completed a best efforts technology development and demonstration program funded by the Defense Advanced Research Projects Agency ("DARPA") to enable the Department of Defense (DoD) to use JP-5/8 heavy fuel in high-powered, lightweight, fuel efficient, four-stroke piston engines by application of the SCAI. The first phase of this program involved a feasibility demonstration of this process by modification of a Subaru 3.0 liter 6-cylinder engine shown in Figure 6 with pent roof combustion chamber and SCAI heavy fuel engine (HFE) matching piston shown in Figure 7.

Figure 6
6-Cylinder Subaru SCS SCAI HFE with Direct Injection, Common Rail

Figure 7
Subaru SCS SCAI HFE Preliminary Piston

To develop a higher power piston, Sonex adapted a 3.2-liter Mercedes Benz (MB), turbocharged, in-line, 6-cylinder automotive diesel engine shown in Figure 8, modified with the SCAI piston shown in Figure 9 for heavy fuel operation and achieved peak power of 253 hp at 4,664 rpm with no visible smoke. Characterization of the SCAI near this power level provided an indication that a lightweight 400 hp HFE could be ultimately achievable in a 3.2-liter engine.

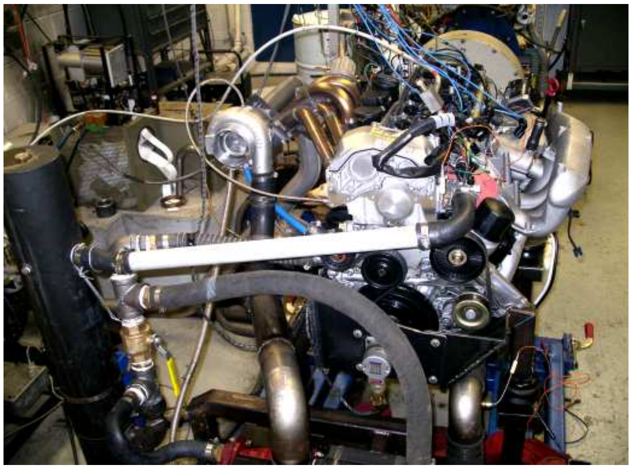

Figure 8
6-Cylinder 250 Hp SCAI HFE with Direct Injection, Common Rail

Figure 9
250 Hp SCAI HFE Improved Piston

DARPA Test Results

A summary of test results at the minimum fuel consumption condition for the DoD SCAI engine shown in Figure 8 is given below in Figure 10, this figure also shows the horsepower at minimum fuel consumption with IMEP from 8 to 12.7 bar. Fuel consumption at 253 horsepower could not be measured due to equipment malfunction. The range of fuel consumption shown falls within that for diesel engines and is approximately 25% lower than for gasoline engines.

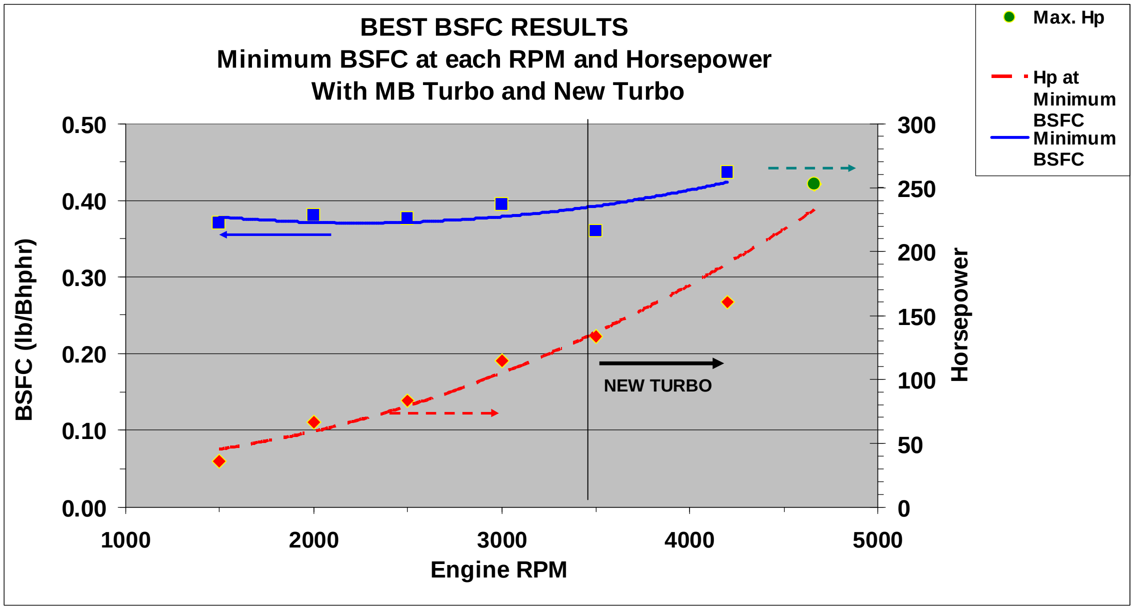

Figure 10
Minimum Brake Specific Fuel Consumption and Horsepower

The turbo boost shown in Figure 11 has already been increased with a minor modification of the exhaust such that higher boost can be attained at high loads. The Lambda (a measure of relative air utilization) shown indicates that even at high loads, the combustion is in the lean-burn mode.

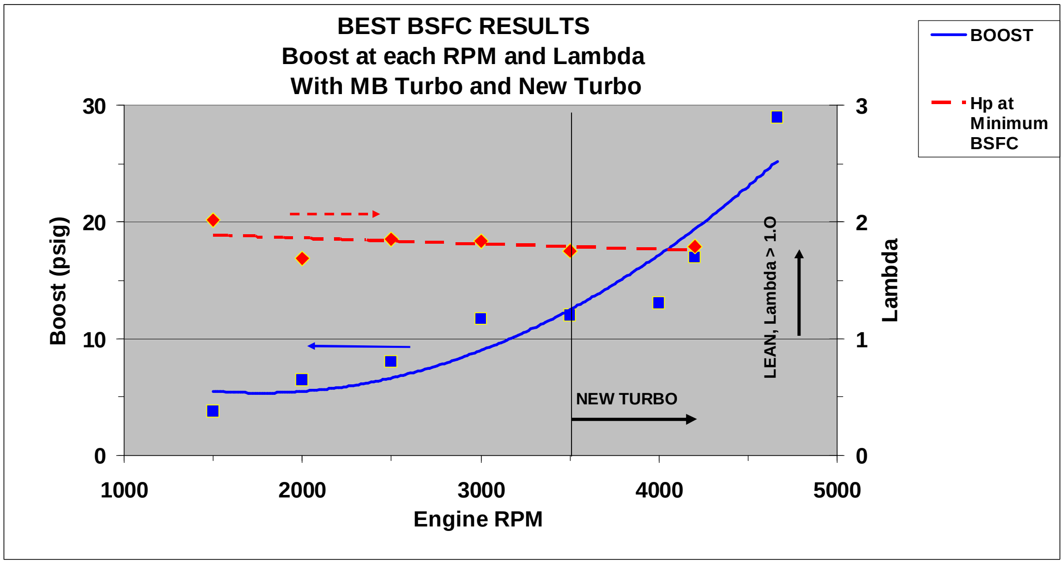

Figure 11
Turbo Boost at each RPM and Lambda

Figure 12 showing the Start of Injection (SOI) and end of injection (EOI) for the main injection providing ~ 70% of the fuel (~30% is injected by the pilot which ends before the SOI, main) indicates that all of the fuel is injected before the Start of Combustion (SOC) ATDC. This is an important distinction from DI diesel combustion where combustion starts before EOI. It also supports the concept of simultaneous ignition of the entire charge, an inherent part of the SCAI process described in Figure 3.

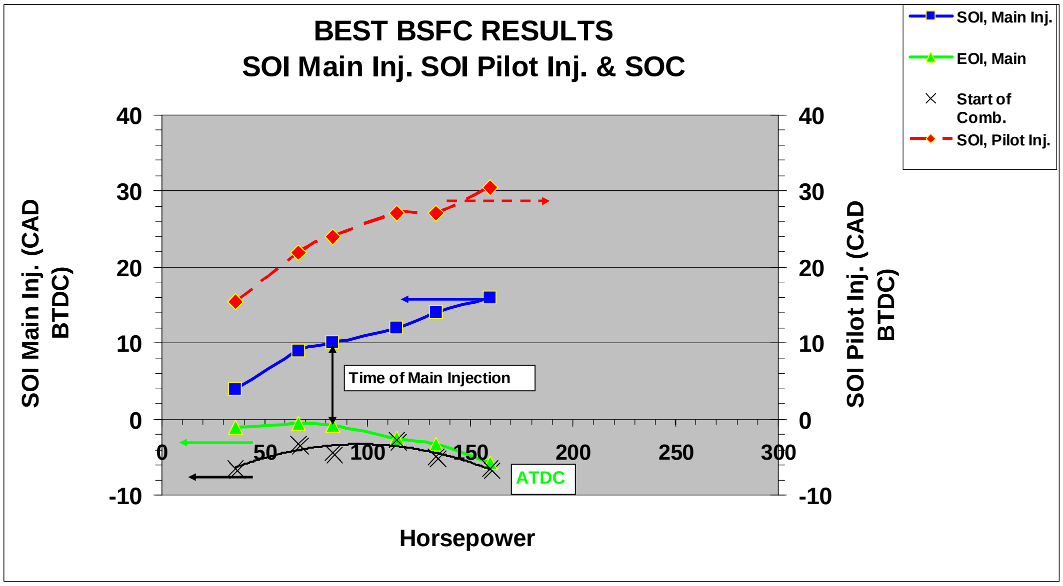

Figure 12
Start of Injection, End of Injection and Start of Combustion

Figure 13 for the maximum cylinder pressure (for IMEPs 8 to 12.7 Bar) and its accompanying standard deviation is shown below. It is seen that the peak pressures are more akin to gasoline engines than to diesel engines. A major objective of radical ignition research efforts is to achieve stable combustion over the full range of engine operation. Here, the average standard deviation is 1.2 bar or 2.2% of the average Pmax indicating good combustion stability.

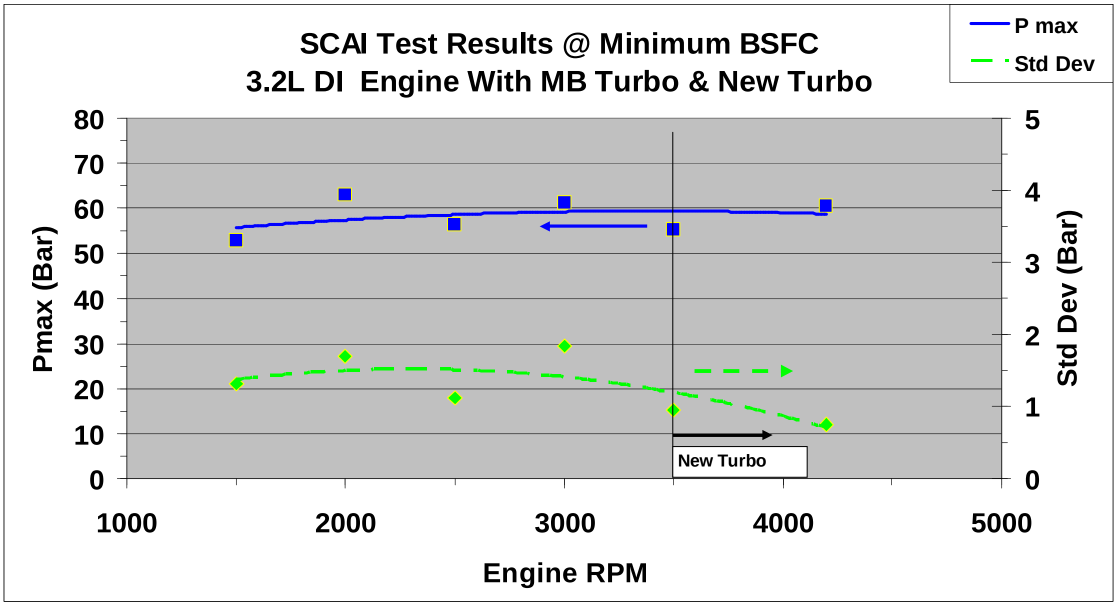

Figure 13
Maximum Cylinder pressure and Standard Deviation of Pmax

The key data at minimum BSFC are included in Table 1 below. Although all the sweeps of the control variables were not completed before the DARPA project expiration date, Sonex intends to continue this work in the future and apply its experience to the use of gasoline with the same piston design. Preliminary data on gasoline SCAI in one of the DARPA engines has already demonstrated the feasibility of using this process with gasoline, again attaining the specific fuel consumption reductions demonstrated with military fuel.

Conclusions

We believe the major conclusions of the DARPA program, as validated by recorded data are:

1. Completion of fuel injection prior to ignition (which occurs after TDC) with a single phase Rate of Heat Release validates the SCAI process.
2. The BSFC attained is below that for gasoline engines and supports the argument for designing light weight SCAI engines with cylinder pressures no higher than those for gasoline engines.
3. The short duration of SCAI combustion as validated by the rate of heat release supports the goal of reaching 400 Hp at high rpm with an engine displacing 3.2 liters.
4. The low CO readings (0.01 to 0.02%) and Lambda readings above 1.5 validate the SCAI as a lean burn process.
5. The SCAI exhaust will be non-visible at higher power with accompanying low hydrocarbon emissions.
6. The SCAI combustion process enables the lean burn of low cetane fuels in moderate compression ratio light weight DI engines with low emissions and fuel consumption akin to that of diesel engines.

The results of this effort could lead to DoD engine programs with Sonex to achieve the transition from operation on gasoline to JP-5/8 heavy fuels in applications such as UAVs, hybrid power trains, tactical all-terrain vehicles, powered parafoil-wings, power boats, etc.

As an outcome of this current effort, it is seen the SCAI lean-burn combustion process also has significant potential for commercial application in the automotive market for gasoline direct injected (GDI) engines to cost effectively improve fuel mileage 25% to 30%. The feasibility of SCAI-GDI has already been demonstrated experimentally and Sonex is actively seeking GDI support.

						Data of 092507 and 091207 at Minimum Fuel Consumption													
Run #	RPM	Timing off	Start,pilot	% pilot	Start,main	Time,main	End,main	Torque	HP	Fuel used	fuel burn	BSFC	BS No	Air Flow	Air Flow	Air Fuel	Lambda	Lambda	SOC	Pmax	AvgEGT
		Offset-cad	cad-BTDC		cad-BTDC	cad	cad-BTDC	(lb-ft)		lb/2min	(lb/hr)	(lb/Hphr)		(CF/HR)	(LBS/HR)	Ratio	measured	from Cal.	cadBTDC	Bar	deg F
5, 9-12-07	1500	11.5	15.5	32	4	5.14	-1.14	125.0	35.7	0.44	13.2	0.3697	0.1	5352	392	29.72	2.02		-6.50	52.89	748
12, 9-12-07	2000	12.9	21.9	30	9	8.40	-0.60	175.0	66.6	0.845	25.35	0.3804	0.5	8598	630	24.86	1.69		-3.25	62.95	890
16, 9-12-07	2500	14	24	30	10	10.81	-0.81	175.0	83.3	1.045	31.35	0.3763	0.7	11652	854	27.24	1.85		-4.50	56.32	932
21, 9-12-07	3000	15.1	27.1	28	12	14.51	-2.51	200.0	114.2	1.500	45	0.3939	1.2	16602	1217	27.04	1.84		-2.75	61.25	1061
2, 9-25-07	3500	13.1	27.1	20	14	17.30	-3.30	200.0	133.3	1.6	48	0.3601	0.3				1.75	1.75	-5.00	55.25	989
10, 9-25-07	4200	14.5	30.5	20	16	21.77	-5.77	200.0	159.9	2.325	69.75	0.4361	0.9				1.79	1.79	-6.50	60.5	1114
						Partial Data due to Combustion Analyzer/Data Acquisition System Failure															
2, 9-26-07	4400				17			225.0	188.5				0.9								1156
1, 9-27-07	4664							284.9	253.0												

Table 1

Data and Calculated Results at Minimum Fuel Consumption