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## SONEX TECHNOLOGY OVERVIEW FOR DIRECT INJECTED ENGINES

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Sonex Research, Inc., 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 conducts basic research into the principles of in-cylinder control of ignition and combustion. By the late 1980's and early 1990's, the development of the Company's patented technology, known as the Sonex Combustion System (SCS), moved in the direction of chemical/turbulent enhancement of combustion for the reduction of emissions and the enablement of a new combustion process for normally aspirated and boosted conditions.

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, direct injected (DI) engines that improves the process of combustion through a combination of chemical and fluid dynamic effects. These effects are enabled by the patented piston technology as shown schematically in the attached figure. The Company believes its SCS accomplishments have the potential to be a four-stroke paradigm shift that will provide enabling capabilities 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 size/weight possible.

SCS DI technology embeds uniquely shaped cavities called micro-chambers (MCs) into the piston around the circumference of the piston bowl. These MCs thus form a segmented ring around the piston bowl, with each micro-chamber positioned in line with a fuel injector spray. The MCs are connected to the piston bowl by tunnel-like vents arranged strategically so that a small fraction of the fuel can be trapped in the MC. The flame from the main chamber is quenched by the vent, preventing complete combustion in the MCs. Only slow and incomplete oxidation (of the trapped fuel) takes place, resulting in the formation of highly reactive radicals and intermediate species. These materials exiting at high velocity are very effective in reducing emissions in standard diesel engines at normal compression ratios; they also provide the means to achieve controlled auto-ignition *at low/moderate compression ratios* with a variation in the basic SCS design.

The Sonex DI technology is applicable over *two distinctive paths*. The first path, the *Low Soot Diesel Design (LSDD)*, enables soot and oxides of nitrogen (NO<sub>x</sub>) 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/moderate compression (<12.5:1) DI engines to enable fully controlled auto-ignition and combustion with single phase high rates of heat release for a variety of fuels. SCAI "spark-less" combustion in un-throttled, DI lightweight engines significantly reduces emissions and has demonstrated *improvement* in fuel economy of 25% to 30%, yet maintaining maximum cylinder pressure of gasoline engines.

**For the LSDD:**

The emphasis is in placing the vent/s (with its high exit velocity jet) for maximum interaction with the soot cloud. During the power stroke, the pressure drops in the combustion chamber more rapidly than in the MCs, and highly reactive gases are expelled from the MC at high speeds into the soot cloud. In addition, the soot level remains at a reduced level when high levels of exhaust gas recirculation (EGR) are used to reduce  $\text{NO}_x$ . The LSDD has been shown to be completely different and more effective than an air cell. Sonex LSDD experience with multi-cylinder turbo-charged engines shows an *overall average cycle* soot reduction of 50% and an accompanied 10% reduction in  $\text{NO}_x$  (without EGR). Significant reductions in  $\text{NO}_x$  can be achieved with common rail control of injection timing and EGR while holding the soot level at the reduced level. Ricardo Consulting Engineers in Europe presented results of their evaluation of a major OEM engine with pre-production LSDD pistons, a computation fluid dynamic (CFD) and gas dynamic analysis at the SAE Fuel and Lubes, May 2002 Conference: SAE 2002-01-1682.

A sample of the calculations from the above SAE paper are shown below in Figure 1 with the soot destruction clearly evident.

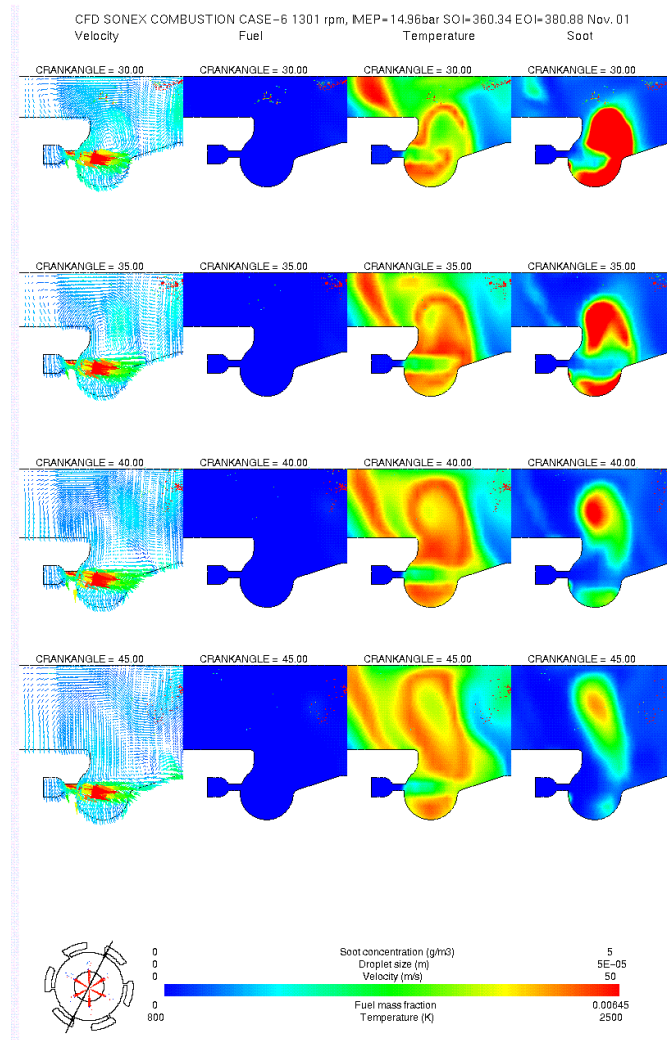


Figure 1

Two sample pre-production Sonex LSDD pistons are shown below for the engine reported on in the SAE article. The first in Figure 2 is a composite with the upper half produced by powder metallurgy, the lower half attached by squeeze cast aluminum. The second in Figure 3 is all aluminum with the upper section containing the micro-chambers attached by electron beam welding. Both pistons were produced by Federal Mogul for a European OEM. Simplified fabrication techniques enabling production *on current piston manufacturing lines* are now being developed.



**Figure 2**  
**SCS COMPOSITE**  
**PRE- PRODUCTION PISTON**



**Figure 3**  
**SCS ELECTRON BEAM WELDED**  
**PRE-PRODUCTION PISTON**

The second design path for Sonex DI SCAI technology offers a paradigm shift in reciprocating IC engines which have generally 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, homogeneous charge CI, (HCCI), etc., this third type of ignition varies from the first two because it employs means for increased control of the chemical kinetics of the overall combustion process. Though these various names may indicate some important differences in the details of these individual combustion approaches, there are commonalities that enable them all to be considered collectively as this third type of IC engine *auto-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*), is found to 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 *fully controllable* auto-ignition over the full range of engine speed and load on low cetane, high-octane fuels such as methanol and gasoline *at compression ratios that are much lower* than normally required for fuels with such poor CI ignitability.

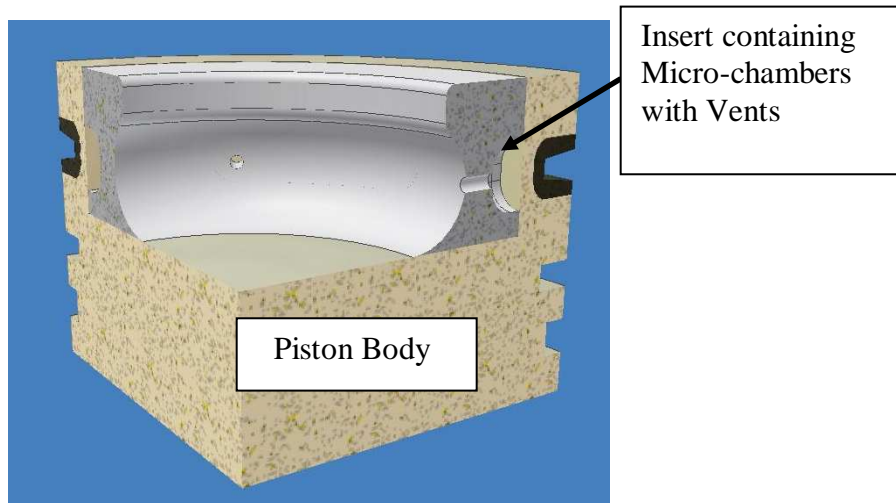
- In the SCAI configuration, the piston MC embodiments produce, conserve and expel the intermediate chemical species and radicals that enable auto-ignition at modest compression ratio. These materials are produced in the micro-chambers as the result of partial oxidation of the small fraction of the injected fuel that has been “captured” (during the compression stroke) and reacted with air (and other in-cylinder gases) on the power stroke. A major portion of the materials produced in the MC exit during the power stroke, however, a fraction of the active intermediate species and radicals are preserved by MC/vent design and retained for addition to the air charge of the next combustion cycle. These species are retained because their chemical activity becomes “frozen” in the expansion (power) stroke as the pressure (and thus temperature) inside the MCs drop sufficiently low. During the exhaust stroke, many of the materials are expelled from the MCs but *the remainder are expelled at the beginning* of the next air intake stroke, as observed in an optical engine and now confirmed by calculation. Thus, these species mix with the incoming air charge. Then, during the compression stroke, as the overall temperature of the air charge increases with crank angle, *these species resume their chemical activity*, which completely alters the chemical kinetics of the following combustion process. Auto-ignition of the main charge is enabled at temperatures of 100°-200°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 burn at lower peak temperatures, thereby achieving a reduction in soot and nitrogen oxide formation (NO<sub>x</sub>). It is in part because of the possibility of operating the engine at lower compression ratios (because of the presence of radicals in the main chamber) that soot production, as well as the oxides of nitrogen, are greatly reduced.

Detailed single cylinder engine results and supporting fluid dynamics and kinetics (KIVA and CHEMKIN code) were presented at the first IFP world congress on HCCI, CAI and RI, Paris, France, November, 2001. More recently, a Sonex full chemical kinetics study accounting for the interactive chemistry processes of both chambers was presented at the Joint JSAE/SAE Fuels and Lubricants meeting in Yokohama, Japan on May 19, 2003 (SAE Paper 2003-01-1788) and was followed several other papers in 2004 (SAE papers 2004-01-1677, 2004-01-1846, 2004-01-1847)

In summary, 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* 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 DI enable low compression ratio auto-ignition and homogeneous (or nearly so) combustion. Homogeneous combustion is evidenced by high rate, *single-phase* combustion at all speeds and loads yielding low NO<sub>x</sub> and soot emissions. An added benefit of the very short heat release is a significant reduction in heat losses to further improve fuel economy.

#### **Note!**

The *licensed* technology Sonex uses in its production 2-stroke engines that operate on “heavy fuels” and are used in UAVs is a derivative of the 4-stroke DI designs but *is not piston based*; these engines have micro-chambers in the cylinder head and other features according to U.S. patent 5,855,192.

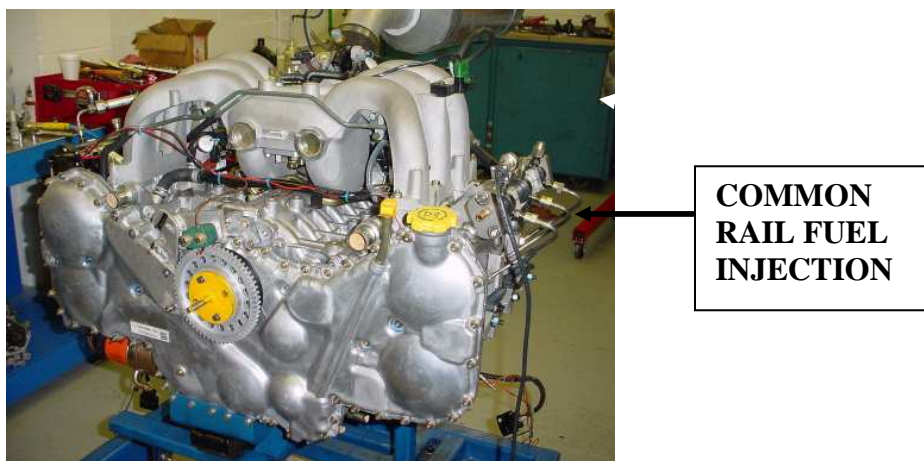


**Figure 4**  
**Per U.S. Patent Number 5,862,788,**  
**Issued January 26, 1999, and others**

Additional SCAI information is available on request for a six cylinder engine using direct injection and common rail in a recently completed program funded by DARPA(Defense Advanced Research Projects Agency). Below is a view of the First Phase engine, Figure 5 and preliminary piston, Figure 6 used in the initial DARPA program. The engine of the final DARPA Phase, Figure 7 uses a piston design, Figure 8, similar to that shown in Figure 4 above and has achieved 253 horsepower at 4400 rpm. Although not yet optimized, the engine operates stably over the entire range and has achieved a maximum rpm of 6300 rpm; Figure 9 demonstrates the power and fuel consumption.

**Sonex Gasoline Direct Injection (GDI) SCAI Design**

A direct benefit of the DARPA program is the first Sonex GDI engine that Sonex is developing. One of the engines employed in that program has been run on gasoline to demonstrate the feasibility of such an engine operating at a compression ratio of 12.5:1 with no throttle, and no spark plug. Using the same SCAI piston designed for military JP5 fuel, a BSFC of 216 g/kWh at a BMEP of 9.5 bar has been achieved in a preliminary investigation.



**Figure 5**  
**Assembled 6-Cylinder Subaru SCS HFE with Direct Injection Common Rail**

**Initial DARPA HFE**



**Figure 6**  
**Forged Aluminum Alloy SCS SCAI HFE Piston**

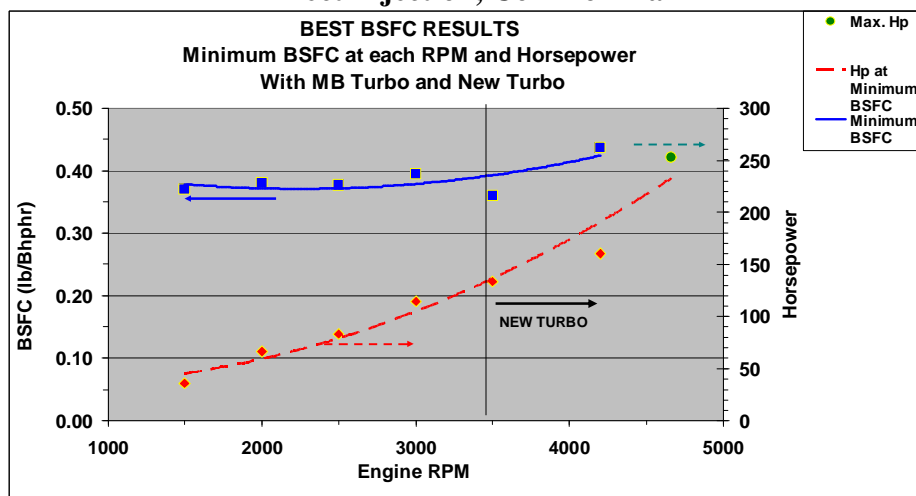


**Figure 7**  
**DARPA 6-Cylinder 250 Hp SCAI HFE**  
**With Direct Injection, Common Rail**



**Figure 8**  
**250 Hp SCAI HFE Improved Piston**

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



**Figure 9**  
**Minimum Brake Specific Fuel Consumption and Horsepower**