

Ultra-Clean Low-Swirl Combustion for Heating and Power Systems

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Lean Premixed Combustion is an Effective Passive Pollution Control Technology

- **Opportunity**

- ▶ Low NO_x due to low flame temperatures
- ▶ Can meet most stringent air quality rules in California (NO_x < 9 ppm @ 3% O₂)

- **Barrier**

- ▶ **Needs robust flame stabilization method to**
 - increase operating range
 - reduce risk of inciting combustion oscillations
 - withstand changes in mixture inhomogeneity and fuel properties

Low-swirl Combustion (LSC) Produces Stable & Robust Lean Premixed Flames

- **LSC is a flame stabilization method discovered at LBNL**
 - Operating principle fundamentally different than that of conventional burners
 - Spin-off technology from DOE basic research
 - Excellent experimental configuration for investigating near limit phenomenon (e.g. lean H₂ combustion)
- ▶ **Technology transfer**
 - 2 US patents
 - Basic knowledge supported development of scaling and engineering rules, and facilitated practical implementations
 - LSC commercialized by Maxon Corp. for direct industrial process heaters (two lines of products)
 - Several hundred units installed with size ranging from 0.6 to 50 MMBtu/hr
 - Demonstrated > 20,000 hr. trouble-free continuous operation
 - Meeting most stringent air-quality rules in US

LSC Has a Signature Lifted Flame



Burner made of PVC to showcase the uniqueness of the LSC concept

- **Low-swirl combustion generates a freely propagating flame**
 - ▶ Patented swirler designed to generate a **divergent flow** where the flame burns at its turbulent flame speed
 - ▶ Supports stable flames over a very large range of mixtures and flow conditions
 - ultra-lean conditions for ultra-low emissions systems
 - ▶ Flame position invariant through wide range of inflow velocities and fuel/air ratios

Patented Vane Swirler for LSC



- Simple design amenable to easy manufacturing using conventional materials
- Governing equation available for scaling to different output power

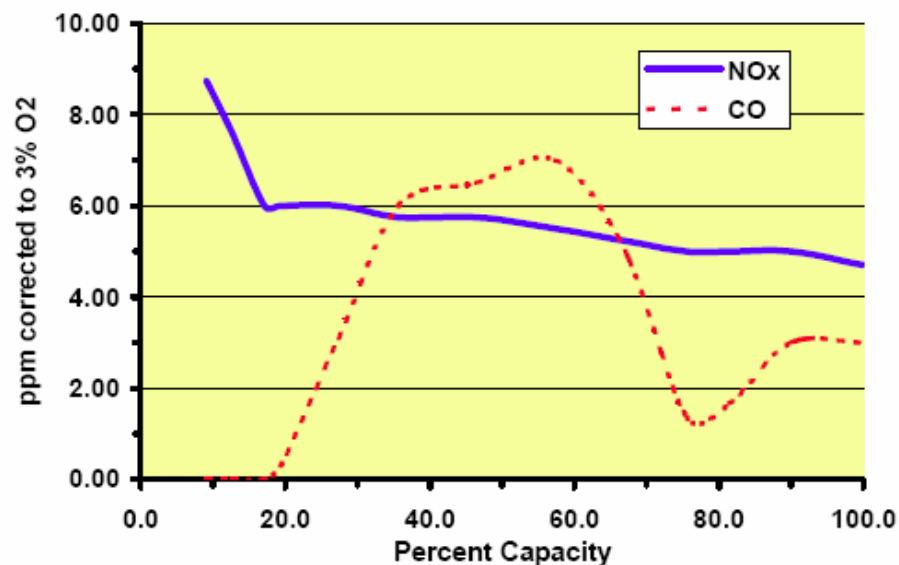


LSC Commercialized for Process Heat

- Maxon Corp. licensed LSB in 2002 for ultra-low NOx burners (< 9 ppm at 3% O₂ guaranteed) for industrial heating, baking and drying
 - ▶ 'Achieved "industry best" emissions without sacrificing cost or performance'
- M-PAKT burners (1 – 6 MMBtu/hr) available since Sept. 2003
 - ▶ 10:1 turndown without pilot assistance
 - ▶ Several hundred units installed
 - ▶ Improve product quality (paint curing & food processing)
 - ▶ 1st unit operating continuously since 2/02
- OPTIMA SLS dual-fuel capable burners (50 MMBtu/hr) since May 2005
 - ▶ enhanced 15:1 turndown
 - ▶ two units installed



Typical Emissions

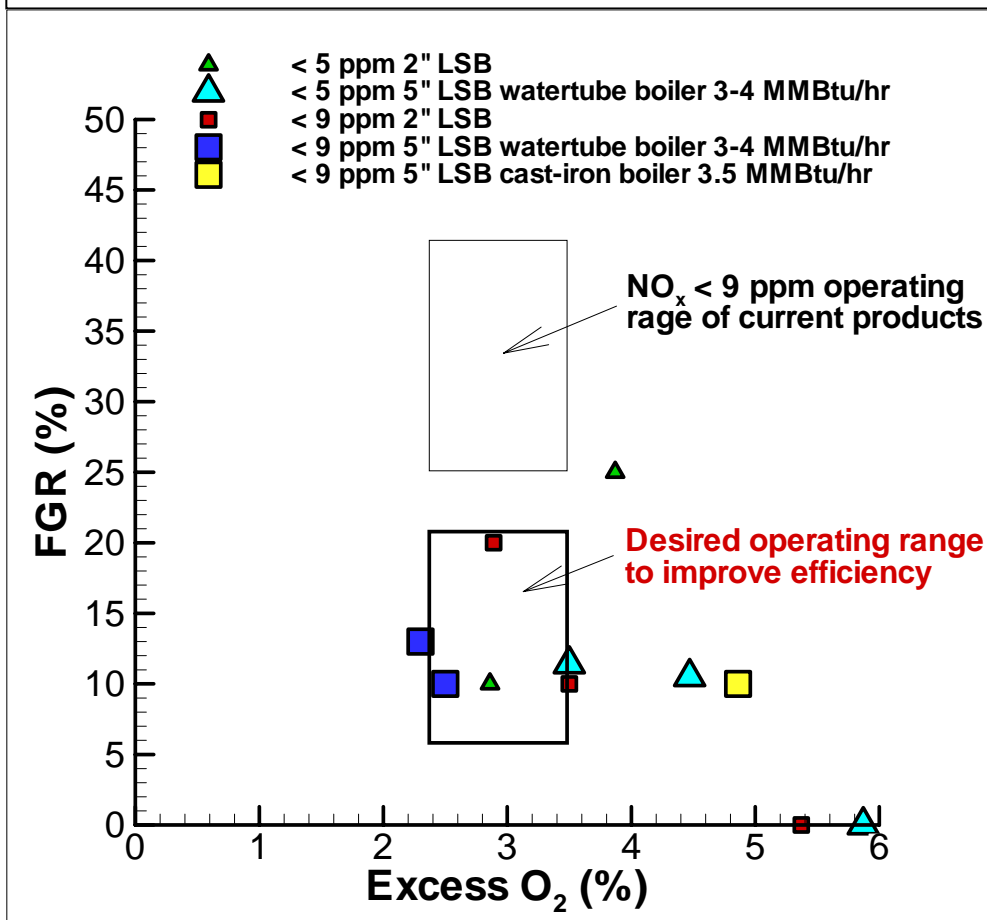


Maxon Identified Significant Economic and Technical Advantages of LSC

- **Design scales by governing equations**
 - ▶ A radical departure from experimentation approach
- **Size compatible to existing equipment**
- **Can be fabricated with no initial re-tooling or new patterns required - fewer parts from common materials**
- **Use existing control for conventional high NO_x burners**
- **Flame is not in contact with burner tip**
 - ▶ No thermal stresses to cause metal fatigue
- **Lower operational cost, and greater ease of operation, thanks to simpler combustion process**

LSC Tested in Commercial Watertube & Firetube Boilers with External FGR

LSC Operating points for < 9 & < 5 ppm NO_x



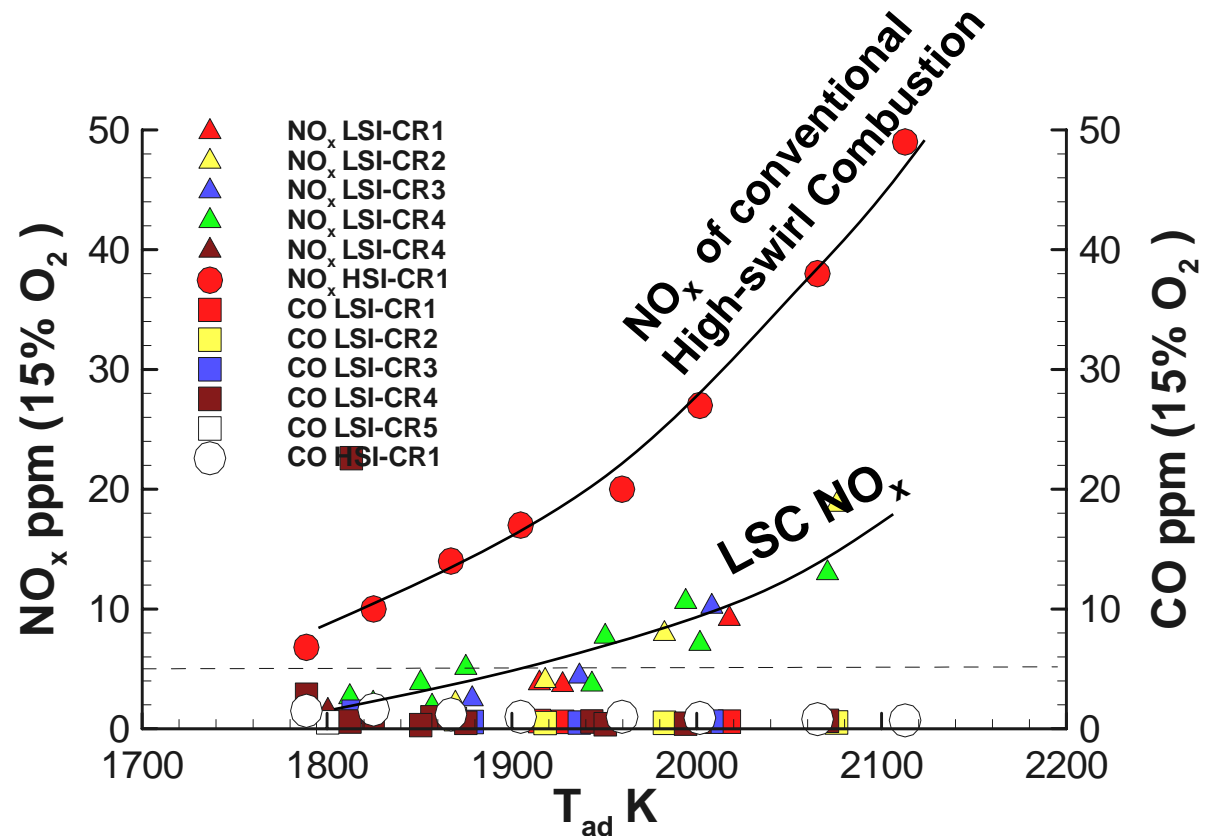
- Use blower and controls for the commercial boiler
- Demonstrated low NO_x at partial load
- LSB shows good promise for improving system efficiency

Low-Swirl Combustion for Gas Turbines

- Stationary land turbines are first to embrace lean premixed combustion as Dry-Low-NO_x
- Air-quality regulations in California and many parts of US require < 5 ppm NO_x @15% O₂
- DOE sponsoring research to develop low-swirl injector (LSI) for 5 to 7 MW engines
 - ▶ Low cost and engine friendly design using existing hardware if possible
- California Energy Commission sponsoring research to develop LSI for microturbines in a combined heat and power boiler system

Low-Swirl Combustion Achieved 2 ppm NO_x in Natural Gas-Fired Turbines

- Developed plug-in replacement for Solar Turbine's SoLoNOx 7 MW engines
- Engine test scheduled for April 2006



Outlook

- **Industrial Processes**

- ▶ **Process heat – develop enhancement methods with Maxon**
- ▶ **Boilers & petroleum refining – seeking development and commercialization partners**

- **Electricity Generation**

- ▶ **Mid-size turbines – begin engine test in Spring 2006**
- ▶ **Micro & utility turbines – seeking research & development partnerships and opportunities**
- ▶ **IGCC turbines – seeking research and development partnerships**

- **Enabling technologies**

- ▶ **Partial reforming – seeking demonstration partners**
- ▶ **Alternate fuels – demonstrated firing with H₂, HC/H₂, biomass & low-Btu fuels. Seeking R&D opportunities**
- ▶ **Prevaporized premixed liquid fuels – Seeking research & development partnerships and opportunities**
- ▶ **Combine heat & power generation – seeking R&D opportunities**