# Texas' Ozone Problem and the Woodward Burner

Woodward Aftertreatment Systems

and Engine Systems Research

February 12, 2008

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# About Woodward

Woodward is a leading independent provider of innovative ***Energy Control and Optimization Solutions*** that enable our customers to successfully compete in a world that requires increasing energy efficiency, reliability and quality, fuel flexibility, and reduced emissions.

Headquartered in Fort Collins, Colorado USA, Woodward serves global markets in the aerospace, electric power, and transportation industries.

# Strategic Focus: Taking Core Technologies to Markets

## STRATEGIC FOCUS: Energy Control & Optimization Solutions

Fluid Energy • Combustion Control • Electrical Energy • Motion Control

### LEVERAGE: Core Technologies

Valves • Servo Actuators • Combustion Sensing • Digital Electronics
Fuel Injection • Electric Actuation • Ignition • Power Electronics • Pumps • AC Measurement & Control

### INTEGRATE: Systems

Fuel Systems • Combustion Systems • Fluid Systems • Actuation Systems • Electronic Systems

### APPLY: OEM & Equipment Packagers

Diesel Engines • Turbines • Gas Engines • Compressors • Gensets • Switchgear • Airframes • Industrial Vehicles

### SERVE: Market Applications

Power • Transportation • Aerospace




# Sales by Markets & Customers

| Aerospace | Power & Process | | Transportation |
|---|---|---|---|




| 35% | 47% | | 18% |
|---|---|---|---|

**Aerospace**

- GE Aircraft Engines
- U.S. Government
- Pratt & Whitney Canada
- Pratt & Whitney
- Rolls-Royce
- Honeywell
- Williams International
- Major airlines worldwide

**Power & Process**

- Alstom
- Caterpillar
- Emerson Electric
- GE Power Systems
- Kawasaki
- Mitsubishi
- Pratt & Whitney
- Siemens
- Wärtsilä
- Yanmar
- Dresser-Rand
- Ebara
- GE Power Systems
- Mitsubishi
- Rolls-Royce
- Siemens

**Transportation**

- Caterpillar
- Caterpillar Kiel
- Cummins
- General Motors EMD
- GE Transportation Systems
- MAN Group
- Wärtsilä
- Yanmar

*FY2007 Net Sales $1.042 billion*

***Woodward customers are the world's leading OEMs in power equipment manufacturing***

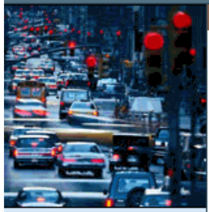
# TERC and Solutions

TERC
Texas Environmental Research Consortium

*Environmental Improvement Through Research*

Air Quality (AQR) | New Technology (NTRD)

> Home > NTRD > Funding Opportunities > RFGAs



**About NTRD**
- Links
- Documents & Presentations

**Research Projects**
- Completed Projects
- Approved Projects
- Diesel Database Project

**Funding Opportunities**
- RFGAs
- SBIR Program

**Technologies**

## RFGA-06

### Development of Technologies to Reduce Oxides of Nitrogen Emissions from Diesel Engines with Low Temperature Duty Cycles

**The submission deadline for this RFGA has passed.**

**Open Date:** August 18, 2006
**Close Date:** October 2, 2006
**Anticipated Number of Awards:** 10 - 20
**Anticipated Award Amount:** $100,000 - $750,000
**Total Funding Available:** $4,700,000

**Related Documents**
- RFGA-06
  Adobe PDF (106 KB)
- Questions & Answers
- Related Forms

This solicitation is for funding the development and verification of technologies that can significantly reduce NOx emissions from diesel engines with duty cycles resulting in exhaust gas temperatures below 225 C for a majority of the time the engine is operating. Similar low exhaust temperatures can occur in cases where available space for installation of exhaust treatment devices is far enough removed from the engine so that a significant portion of the exhaust thermal energy is lost. While the primary objective is the reduction of NOx emissions, special consideration will be given to solutions reducing Particulate Matter emissions as well. Examples of technologies that may provide a solution to light duty cycle temperatures or otherwise resulting low exhaust gas temperatures include, but are not limited to: hybrids, exhaust gas recirculation, low temperature after-treatment devices, or devices used to elevate exhaust gas temperatures to increase effectiveness of more conventional after treatment devices. Examples of potential on-road applications include refuse haulers, school buses and delivery trucks. There are also significant opportunities for off-road applications including construction, marine and locomotive diesel engines.

### Objectives

The overall objective of the NTRD program is to increase the commercial availability of verified emission reduction technologies that reduce NOx emissions in Texas' non-attainment areas. Each project funded under this solicitation should result in a verified commercially available technology that will reduce NOx emissions for non-road, on-road, marine/port, or locomotive applications.

This solicitation covers the following areas of interest:

- Development and verification of low temperature catalysts (e.g. SCR, LNT, LNC)
- Development and verification or extending verification of engine retrofit kits resulting in a minimum 25% NOx reduction
- Development and verification of technologies that raise exhaust gas temperature to enable after treatment technologies
- Other innovative solutions that will result in NOx and other emissions reductions from the targeted diesel engines

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# Alternatives to Reduce NOx

- Three approaches considered
  - NOx adsorbers use catch-and-release to reduce NOx
    - Conversion efficiencies up to 90%
  - Lean NOx catalysts use fuel-rich exhaust
    - Conversion efficiencies < 25%
  - SCR – Selective Catalyst Reduction uses urea
    - Conversion efficiencies up to 90%

- Woodward is focusing on a burner for this approach

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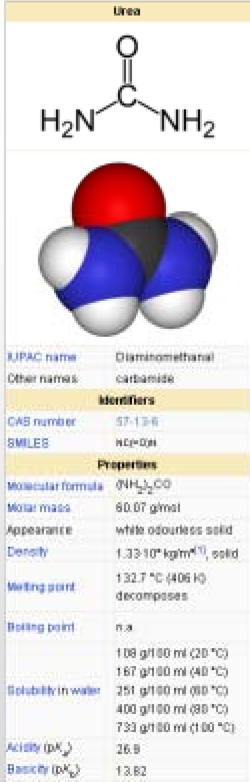
# Brief Introduction to SCR Systems

- Diesel engine exhausts are lean – they contain oxygen
- Difficult to remove oxygen from NOx in this environment
    - NOx is made up of ~90% NO and 10% $NO_2$
- Add a *reducing* agent to remove the oxygen
    - Reducer of choice is ammonia
    - Delivered in the form of an aqueous solution of urea, $(NH_2)_2CO$
- Thus it is called ***S**elective **C**atalyst **R**eduction*




- The basic equations governing SCR reactions are as follows:

$$4NO + 4NH_3 + O_2 \text{ --------> } 4N_2 + 6H_2O$$
$$2NO_2 + 4NH_3 + O_2 \text{ --------> } 3N_2 + 6H_2O$$

# SCR System Operation

- SCR systems are affected by composition of exhaust
  - Balance between NO and $NO_2$ of little concern if temp ≥ 300°C
  - Without a burner would need a DOC to convert NO to $NO_2$

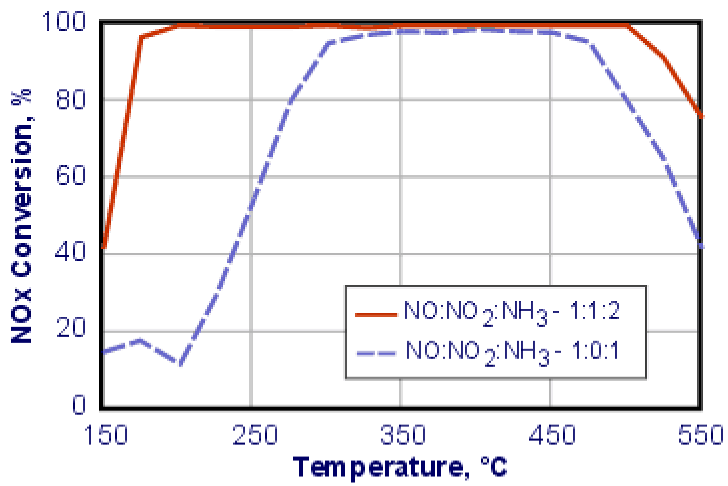



**Figure 6.** Effect of $NO_2$/NO Ratio on $NO_x$ Conversion in $V_2O_5$/$TiO_2$ Catalyst

Source:DieselNet.com

# SCR System Operation

- SCR systems are temperature-sensitive
  - Exhaust temperatures ≤ 225°C
  - Burner output ≥ 350 °C

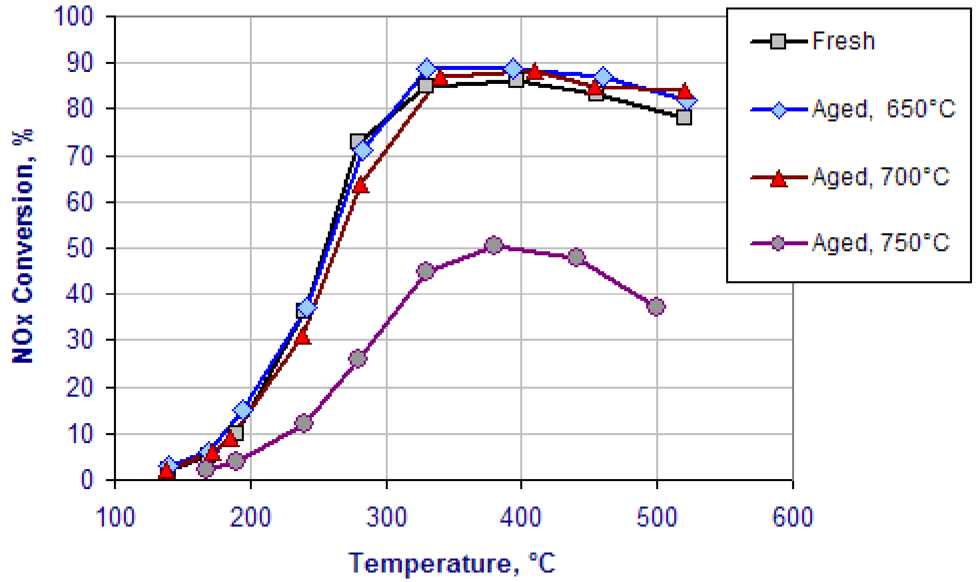



**Figure 5.** Thermal Aging of $V_2O_5/WO_3/TiO_2$ Catalyst

*100 hours furnace aging in 10% $H_2O$, 20 ppm $SO_2$, air*

Source:DieselNet.com

- DPF-out temperature controllable to keep SCR-in temperature <700°C

- Over 300°C conversion rate is >35% even in over-temperature, aged system

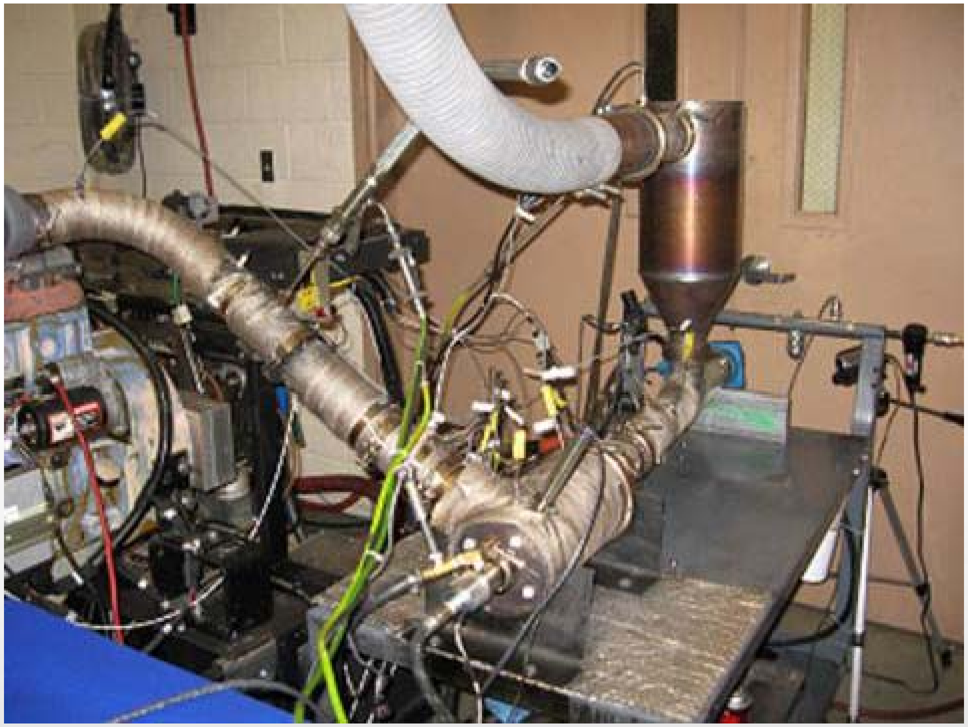
# Woodward's Burner

- Objectives for diesel burner in exhaust
  - Raise exhaust temperature to:
    - ≥ 300°C for SCR applications
    - ≥ 600 - 650°C for DPF applications (~15 minutes every 4 hours)
  - Modulate the burner to maintain these temperatures across the speed/load range
  - Minimize fuel economy penalty for best NOx reduction
  - Minimize burner-out emissions
- Woodward partnering with Tenneco
  - Tenneco to be manufacturer
  - Tenneco (CCA) supplying SCR systems

***Woodward's Phase 2 for HARC is development of a POC burner***

# Woodward's Facilities

- Multiple dyno cells with burner testing currently on two different engines

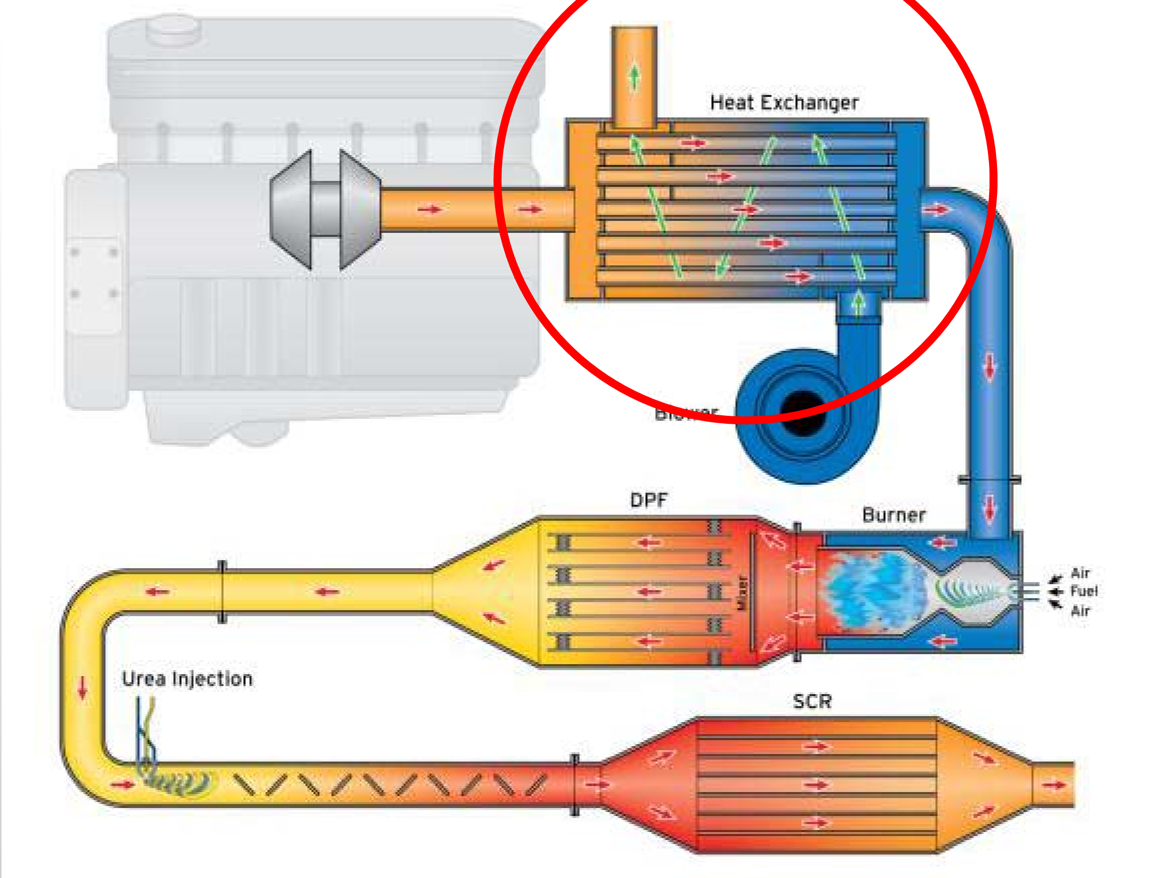


- Fully instrumented

- Key emissions measured

# Woodward's Facilities

- HARC project requires cooling exhaust to emulate low-temperatures



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# Burner Development

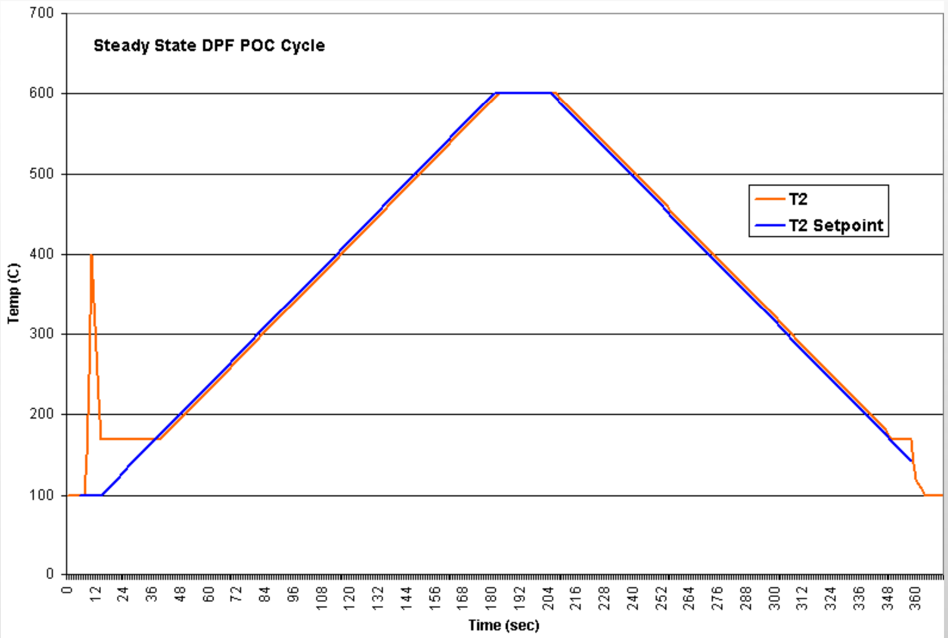
- Diesel burner challenges
  - Operating with variable exhaust oxygen
    - Diesel exhaust oxygen varies from 18% to 5%
    - Minimize external air supply
  - Ensure combustion is occurring
    - Use ion sensing for high-speed flame detection
    - Flameout leads to unacceptable emissions
  - Minimize backpressure
    - Require some backpressure for good mixing/combustion
    - Too much backpressure adds to fuel penalty
  - Uniform outlet temperature
    - Avoid hot-spots into DPF or SCR
    - Uniformity adds to pressure drop
  - Burner skin temperature must be under 400°C

# Burner Development

- Key results from recent testing – 3.0 L engine application
  - DPF application requires higher temperature than SCR
    - DPF regeneration more difficult to achieve than SCR operation
    - Light-off achieved over entire speed-load range
    - Operation at 650°C over entire speed-load range
  - Emissions out of burner
    - NOx approximately neutral
    - HC slightly higher, with several test points higher
    - PM is mostly reduced by the burner, with one test point that is higher
  - Burner fuel from engine supply has no effect on engine operation
  - Burner pressure drop within design range
  - Outlet temperature distribution slightly greater than target

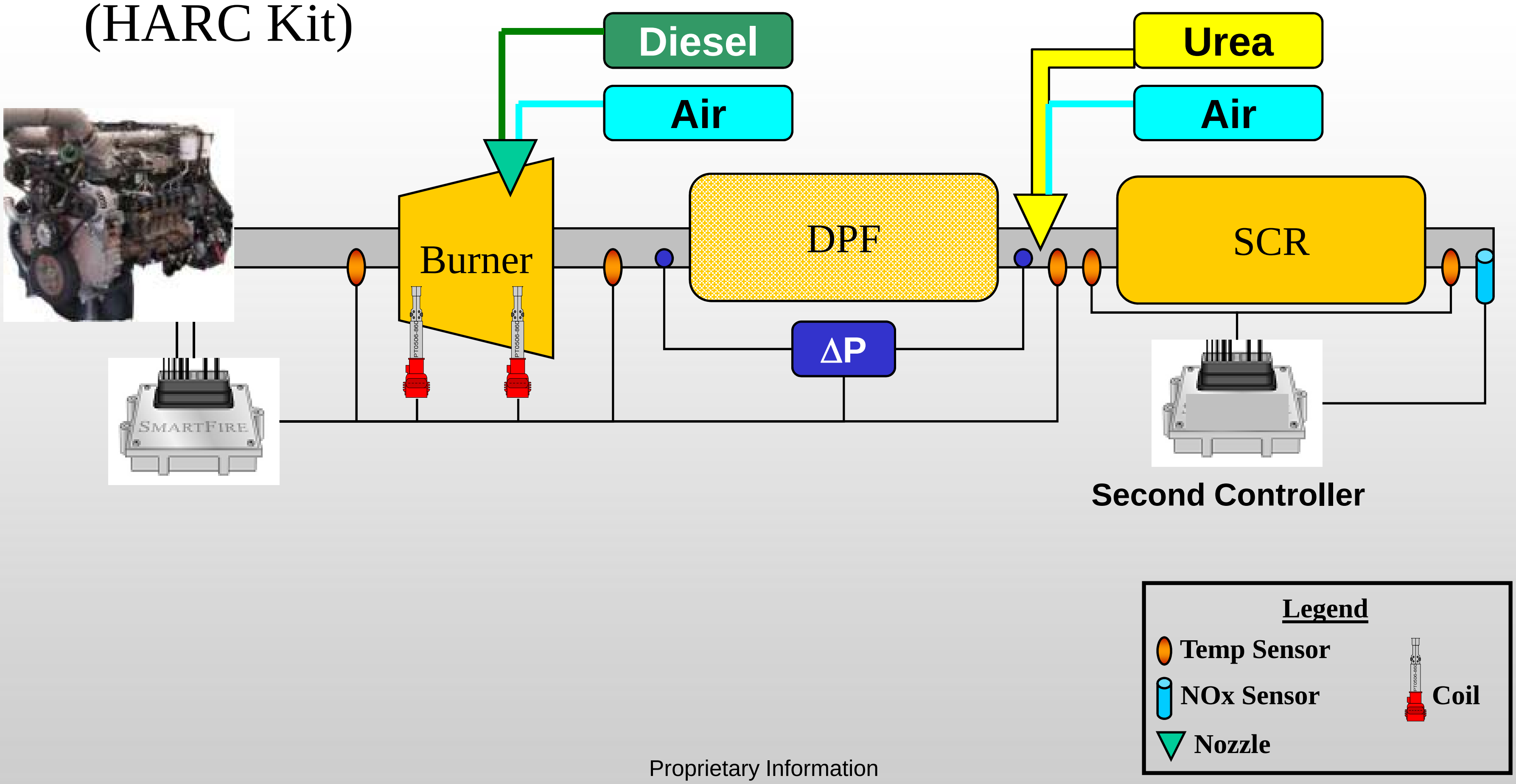
# Burner Development - continued

- Key results from recent testing – 3.0 L engine application
  - Transient testing
    - Able to maintain stable flame throughout transient
  - DPF regeneration control
    - Able to ramp up, hold temperature and ramp down over specified periods



# Aftertreatment Platform

DPF Burner & SCR System (HARC Kit)



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# After Proof-of-Concept

- Phase 3 for HARC will include:
  - Redesign for production
  - Field testing to validate real-world operation
    - Two vehicles for 125 – 1,000 hours of field use
  - Shake and vibration testing at Tenneco
- Pre-Phase 3 need: confirmation that fleet vehicle selected has duty cycle that fits HARC need
  - Woodward will instrument one vehicle to obtain duty cycle

# Summary

•Woodward's burner development progressing very well

•We need to identify a suitable fleet for field testing

•Operational data on the field fleet is needed by August '08

•Questions/discussion

•Thank you

# Putting the HARC system Together