Catalytic Glow Plugs for Natural Gas DI engines

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Westport INNOVATIONS INC.

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Catalyst-coated glow plug shields appear to be a cost-effective means of improving ignition in direct-injection natural gas engines.

- This project was directed at improving the ignition system of a fuel efficient, low maintenance, low emission direct-injection natural gas (DI-NG) engine.
- Engine performance testing showed that properly designed and applied shield coatings significantly improve ignition at high loads.
- Characterization of shield surfaces indicates that the catalyst coatings can survive extended exposure to high temperature oven conditions, but engine tests are needed to verify these results.
- Microkinetics modeling of the observed performance of the shields suggests directions for additional improvements.
- Cost assessment of the preferred shield embodiments indicates that a catalyst-coated shield can be designed to be economically feasible.

This project was directed at improving the ignition system of a fuel efficient, low maintenance, low emission direct-injection natural gas (DI-NG) engine.

- Westport's direct injection system enables natural gas operation over the Diesel cycle and therefore enhances the use of natural gas in vehicular applications:

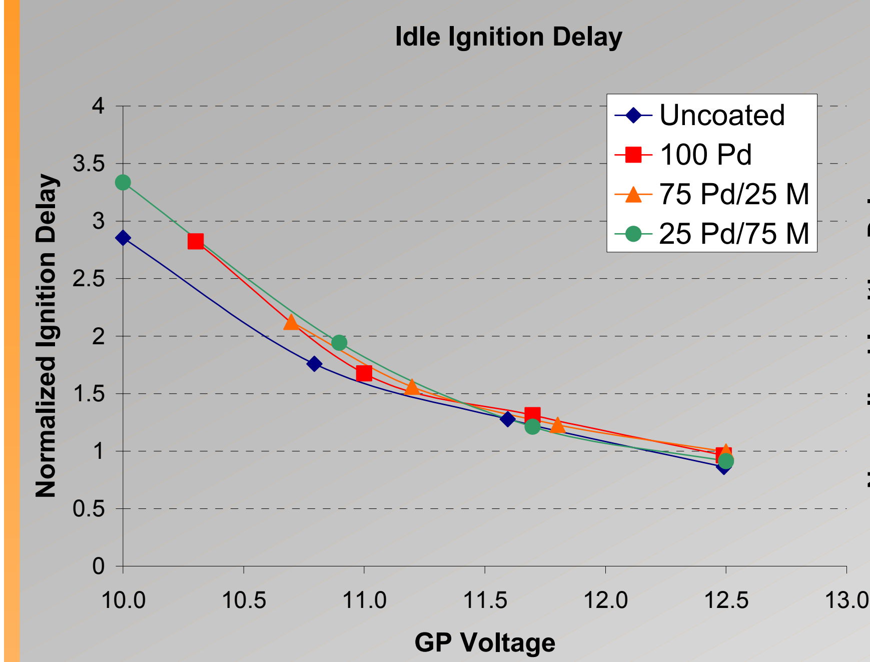
	DI-NG	PFI-NG	DI Diesel
Fuel Economy	+	-	+
Engine Conversion and Maintenance	+	-	+
Smoke Control	+	+	-
Low Emissions	+	+	-

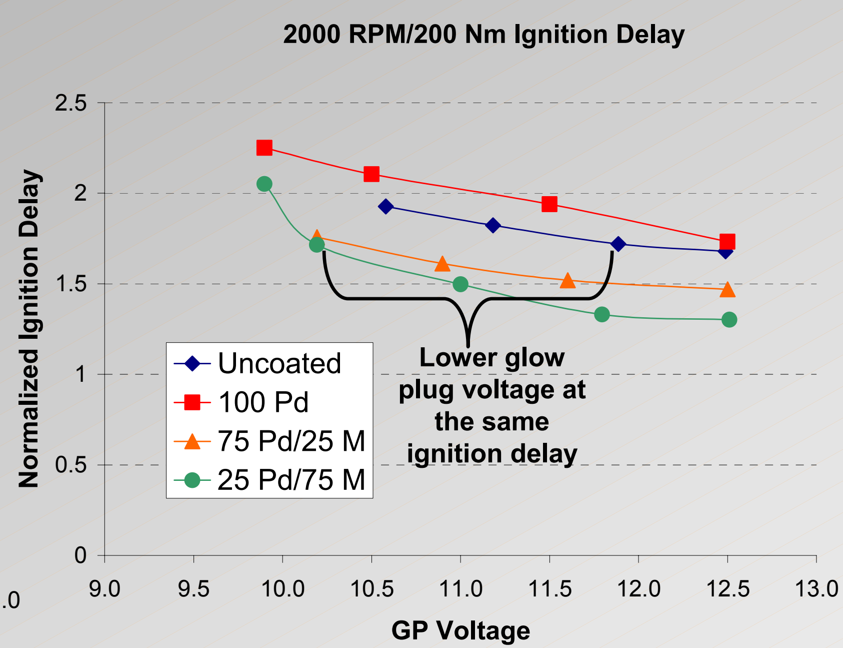
- Hot surface ignition is the preferred combustion actuating mechanism for realizing the benefits of DI-NG:
  - Lower cost and easier packaging than dual fuel, pilot injection for compression ignition.
  - Present 100% of the time so ignition is not sensitive to timing.
  - A large area, so spatial dependency of the fuel injection pattern is reduced compared to a spark.
- However, current surface ignition systems do not meet customer expectations for durability and reliability under continuous use.

Engine performance testing showed that properly designed and applied shield coatings significantly improve ignition at high loads.

- As part of the program, several engine and shield hardware configurations were varied to identify geometric and chemical means of ignition improvement.
- The effectiveness of the catalyst coatings was significantly improved by coating the inner and outer surfaces of the shields.
- Tests with several different catalyst coated shields indicate that Pd/M (another metal) coated shields with high M content are preferable for improving natural gas ignition.

Additional engine tests show that Pd/M coated shields with high M content are preferable for improving natural gas ignition at load.





- **At low load operation, the catalyst coatings do not impact the ignition quality compared to the uncoated case.**
- **At high load operation, the improved stability and lower voltage operation associated with the 25 Pd/75 M shield implies the potential for improving glow plug life.**

Microkinetics modeling of the observed performance of the shields suggests directions for additional improvements.

- Microkinetics models of methane ignition over Pt and Pd catalyst surfaces were developed using Bistro™ and validated against published data.
- With an extended network (to include methane oxidation on Pd/M) we showed that:
  - Alloying, particularly with M is beneficial
  - Low λ is beneficial
  - There is an optimal glowplug temperature
  - Shield mass makes little difference in impacting ignition.

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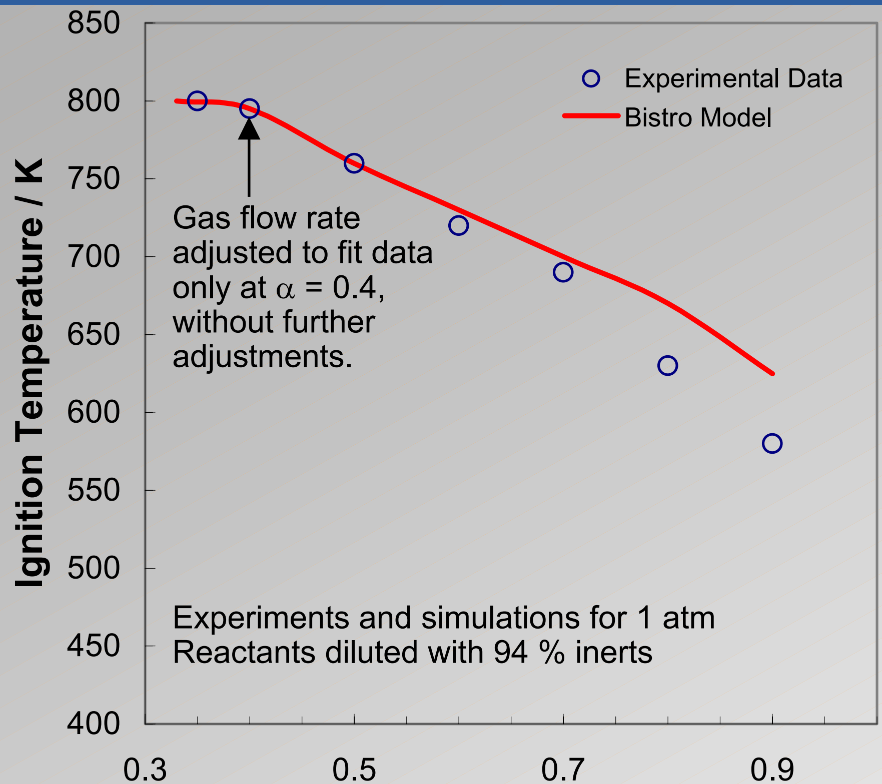
Effect of Concentrations on Ignition Temperature



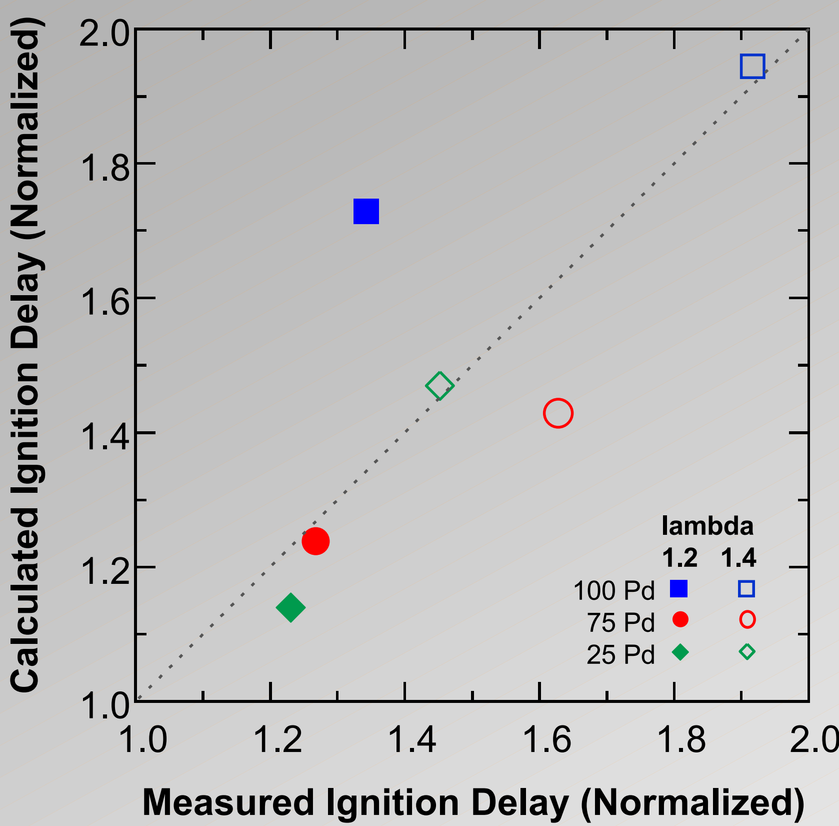
$$\alpha = \frac{P_{CH_4}}{P_{CH_4} + P_{O_2}}$$

Notes

- In the experiments, the catalytic ignition temperature was measured for stagnation point flow of the reactant mixtures over a platinum foil.
- For the Bistro simulations, we approximated the experiment as the catalytic ignition temperature for flow of reactants through a cylinder made of a 50 μm thick platinum foil.
- For the Bistro simulations, the reactants' flow rate was adjusted so as to match the calculated ignition temperature for α = 0.4 with measured; *no further parameter adjustments were made.*
- Exptl. data from: F. Behrendt, O. Deutschmann, R. Schmidt, J. Warnatz, in *Heterogeneous Hydrocarbon Oxidation*, ACS Symposium Series, 1996.

In agreement with measurements, model results show that high M content (in Pd/M catalysts) and low values of lambda reduce the ignition delay.

Comparison of calculated and measured ignition delays



Assumptions for the Simulations

- Ignition delay was defined as the time required for the initial temperature to increase by 10 % over the initial value
- Initial solid temperature and inlet gas temperature = 1500 K
- Experimental data: Single cylinder, 50 and 200 NM torque
- The model correctly predicts the reduction in ignition delay with increased M content.
- The model also correctly predicts the reduction in ignition delay with increasing lambda for each shield coating.

The initial work demonstrated the promise of catalyst coated shields and provided direction for optimization work that is ongoing at Westport.

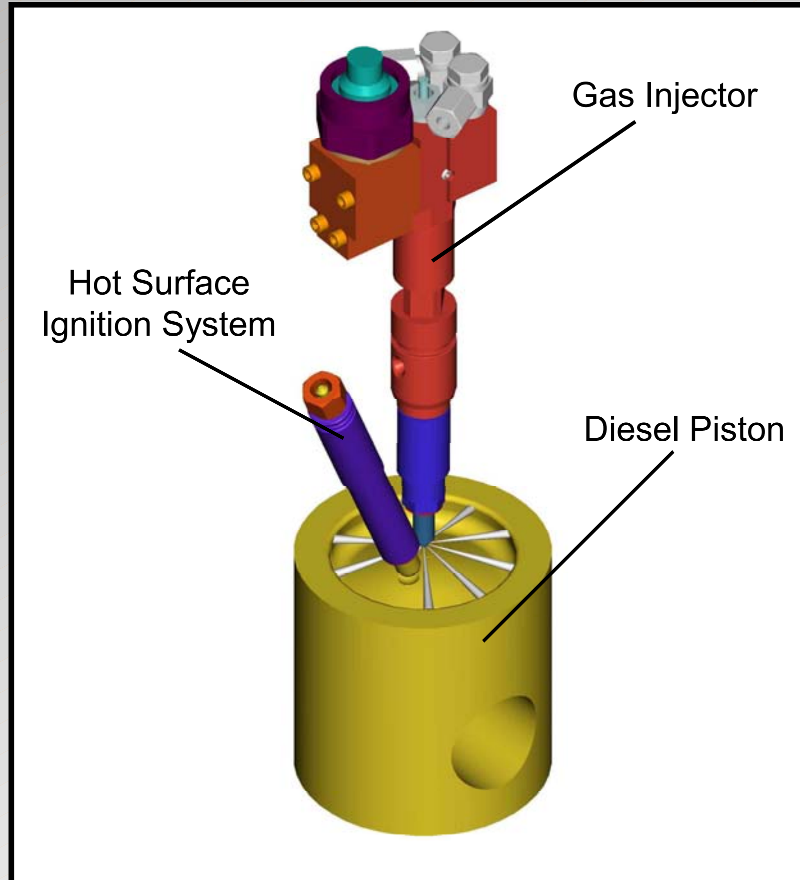
- Further improving catalyst coated shield designs for better ignition performance and meeting emissions targets at low loads will be an important milestone in proving this technology.
  - The coating composition can be tuned for longevity, stoichiometry of the combustion mixture, and temperature.
  - Microkinetics modeling is a useful tool in providing insight into the catalytic combustion process and can be further used to expedite the tuning of future catalyst formulations.
- Since Fall 2002, Westport has independently continued to develop the glow plug ignition concept, with a focus on:
  - Understanding and refining combustion mechanisms
  - Understanding glow plug ignition mechanisms
  - Understanding glow plug material aging mechanisms

Recent Combustion and Ignition System Improvements

- Since completing the initial efforts (under the contract) on catalytic coatings, further work has resulted in significant improvements to the base ignition and combustion system. This work was started in late fall 2002, and is ongoing through 2003 at Westport.
  - Glow plug shield design (patent pending)
  - Injection rate-shaping /multi-injection (with magnetostrictive / piezoelectric variable lift control of the direct acting injector – also patented).
  - Effort has been placed on achieving diesel-like combustion behavior (diffusion burning).
- As well, a fundamental investigation into the aging behavior of production glow plugs was undertaken.
  - Test rig work
  - Initial engine degradation work
- This new work will benefit further development efforts with catalytic coatings.

Improved Ignition & Injection Process

- New ignition hardware has been developed to reduce the amount of fuel which can premix during the ignition delay.
- This design also shortens the ignition delay and lowers required glow plug power by 40% at some conditions.
- This also assures more complete ignition of all fuel spray plumes, especially at light loads.
- It is expected that these improvements will allow us to better demonstrate the benefits of catalytically coated glow plug shields.



Improved Ignition & Injection Process

- These changes to the ignition system allow the fuel to burn in a more diesel-like manner. Ignition can start before injection is finished and this significantly affects combustion behavior.
    - Better cyclic repeatability
    - Improved propagation of flames and control of burn rate.
    - Combustion rate can be controlled by injection rate.
    - For example the injection process can be tailored for low combustion noise – especially important at idle.
- This type of ignition when combined with catalyst coating will be most beneficial. We are looking forward to further optimizing the injection process by using:
    - Rate shaping (low initial rates of injection to allow catalytic reactions to take place at lower glow plug temperatures followed by the main injection).
    - Multi-injection techniques.

Improved Ignition & Injection Process

2000 RPM / 7 bar BMEP – 200 Cycles

Old Combustion System

•Combustion starts after injection process is over

•High cyclic variability

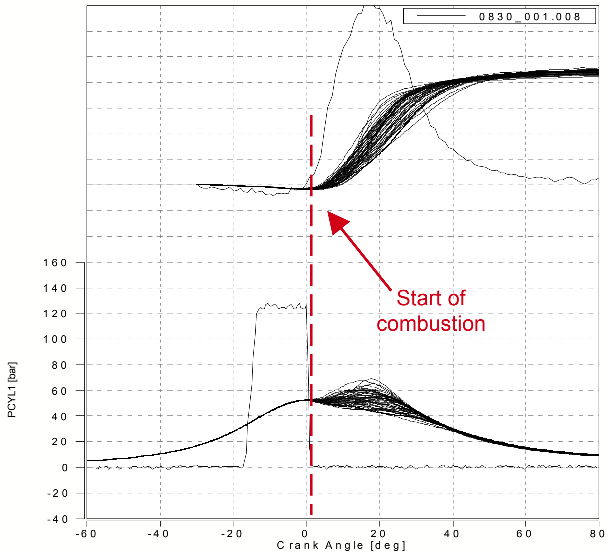
•Pre-mixed combustion

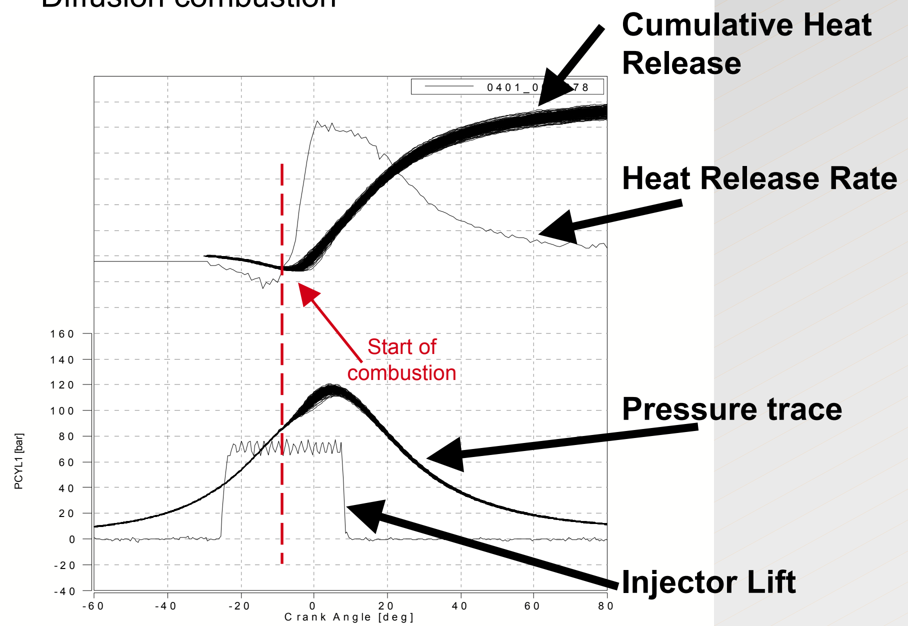
New Combustion System

•Combustion starts during injection process – like a diesel

•Low cyclic variability

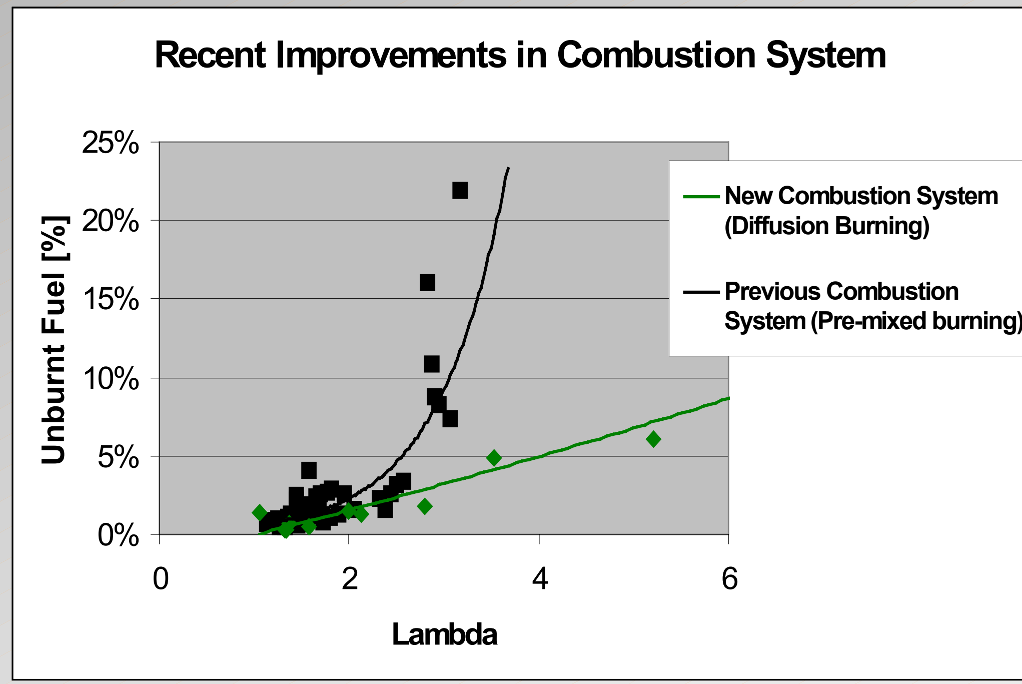
•Diffusion combustion





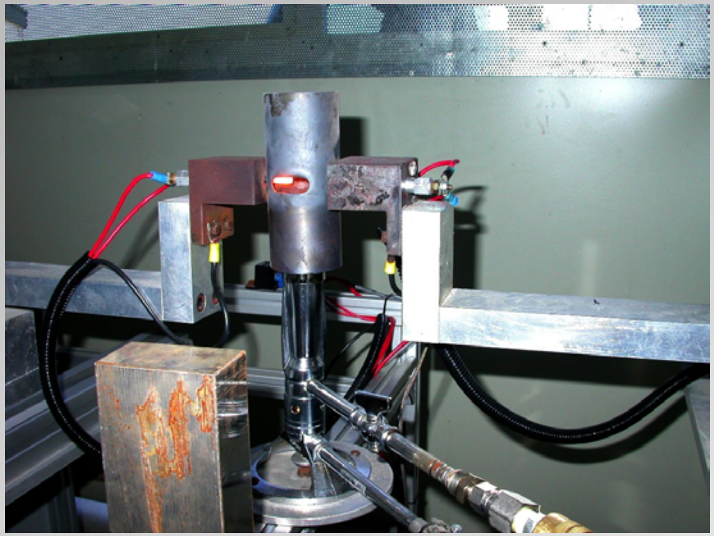
Benefits of Improved Ignition & Injection Process

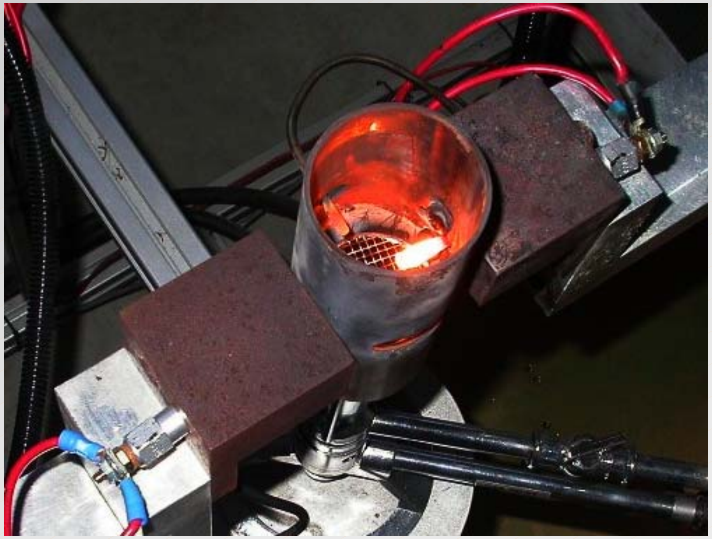
- Combustion efficiency is higher because high-turbulence gas spray plumes have active burning regions at CNG jet/air interface
  - This minimizes formation of lean pockets before combustion starts
  - More complete ignition / combustion of fuel, especially at light loads – leading to lower THC.
  - Again, light load cyclic stability is improved.



Thermal Aging of Glow Plugs

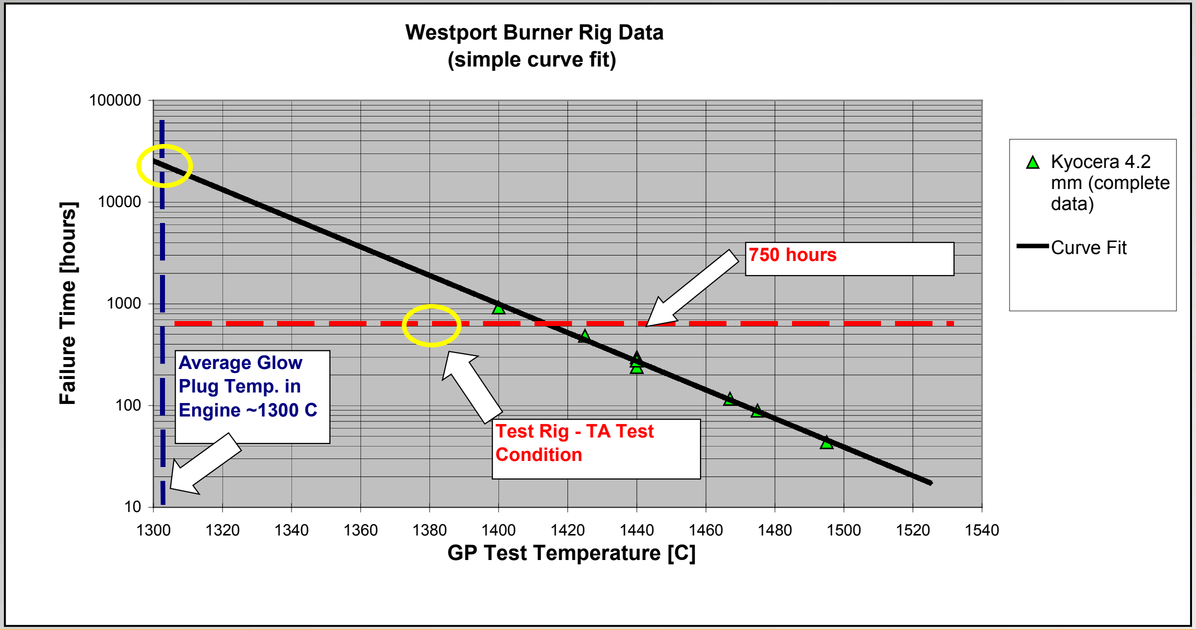
- Thermal aging studies with ceramic glow plug (Si_3N_4)
  - Goal of work was to develop an model which can help predict material behavior.
  - Test rig work uses atmospheric burner flame and can simulate any temperatures of 1600º C or less.
  - For reference, typical engine operating temperature (without a catalyst coating) is approx. 1300º C.
  - Rig does not replicate all engine conditions, however, it allows us to understand temperature and fuel chemistry effects – mainly oxidation.





Thermal Aging of Glow Plugs

- **Initial burner rig results**
  - Very good fit to classic Arrhenius-life temperature model. E= 8.3 eV for current Si_3N_4 glow plugs.
  - 100 C reduction can increase life by 30X approx.
  - Test rig hours have not yet been correlated to engine directly but similar slope in curve is expected with offset.



$$\tau := A_1 \cdot e^{\left(\frac{E}{k \cdot T}\right)}$$

Where:

A_1 is a factor related to geometric shape of the part, flow field, and concentration of chemical species, [hours]

E is the activation energy [eV]

k is Boltzmann's constant 8.617 x 10^{-5} [eV/K]

T is temperature [K]

Conclusions / Future Plans

- Advancements in combustion strategy will be beneficial to further catalytic coat work.
  - New injection and ignition technology will create better conditions to evaluate catalytically enhanced combustion.
  - Additional catalytic shield test work has been planned for 2003 at Westport.
  - Precision Combustion Inc. (North Haven, CT) will be providing a robust catalyst coating technology which was developed for metal substrates. They have significant experience in this area and also work extensively with methane catalysis.
- Aging tests in rig, although not yet directly correlated to an engine provide sound feedback (degradation model) and is invaluable to program status and direction.
  - Development of new rig degradation tests and correlation to engine is underway
  - This work will give us confidence in estimating glow plug life on real-world engines.
- Finally, Westport is considering possible application of glow plug technology to hydrogen or hythane in DI engines. Catalytic coating efforts will likely be beneficial in this area too.

Acknowledgement

- TIAX, Westport and Ford express there sincere thanks to DOE/NREL for support of our work completed during this phase of the NGNGV program