

The Effect of Autoignition-Promoting Additives on Deflagration-to-Detonation Transition

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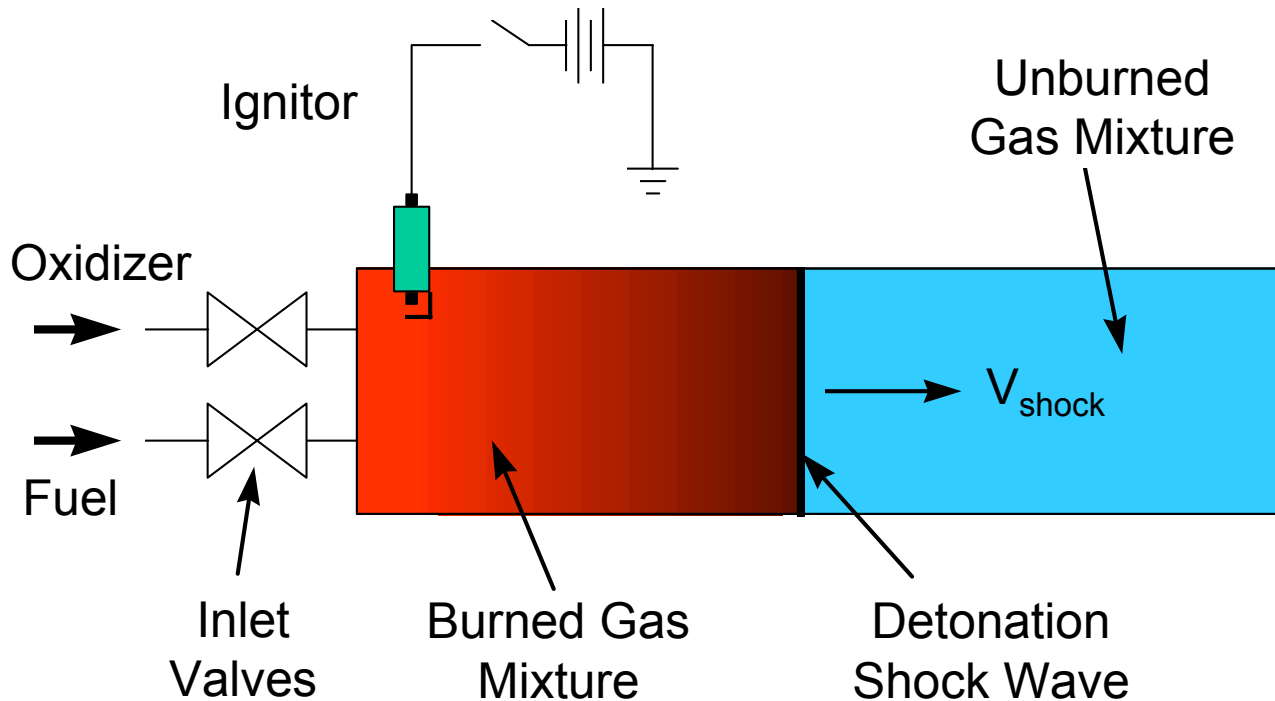
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NASA SBIR Phase I

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Introduction



The Pulse Detonation Engine

- higher specific impulse
- higher thrust/weight
- lower part count

Introduction

- **Unsteady combustion process**
- **Airbreathing with hydrocarbon fuels is desired vs. using H₂**
 - High density = small tankage
 - Existing infrastructure
- **Unfortunately:**
 - Hydrocarbons have longer ignition delay and reaction times
 - Higher ignition energy requirements
 - Narrower detonation limits
 - Longer deflagration to detonation lengths
 - Harder to establish the detonation wave

Introduction

- **Oxygen enriched predetonator tubes have been employed for ignition**
 - Lengthens & complicates the engine
 - On-board O_2 is a hit on I_{sp}
- **Simple low-power spark ignition with rapid DDT is desired**
 - long DDT lengths observed with ethylene/air after spark ignition
- **Solving the ignition problem could be the key to making the PDE a success**

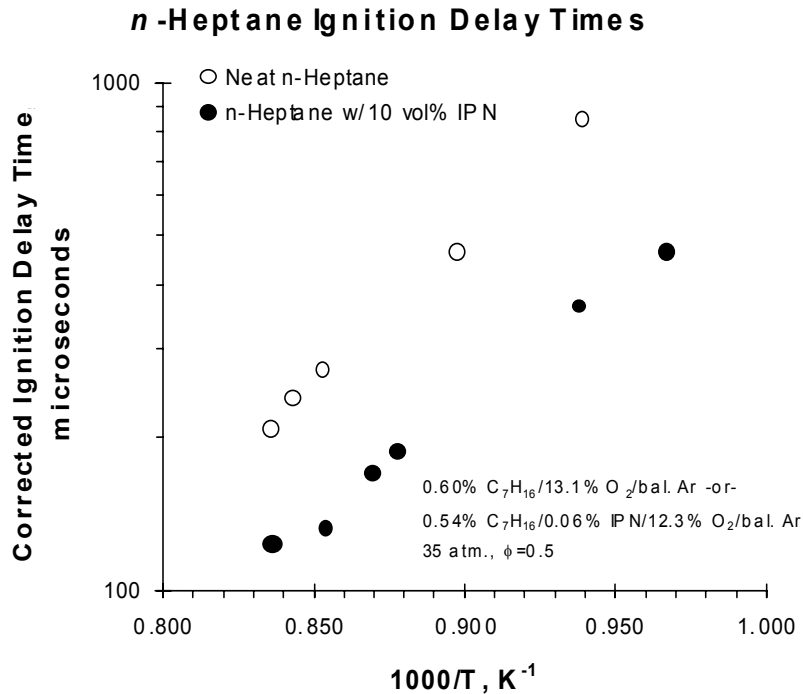
TDA DDT Reduction Approach

- Low-energy spark ignition starts a deflagration
- Deflagration transitions to a detonation under confinement
- Some observations (e.g. Oppenheim et al.) have indicated an initial “slow” flame propagation, then autoignition of the mixture ahead of the flame
- Use of autoignition-promoting compounds could sensitize the mixture = **Reduced DDT**

Phase I Work Plan

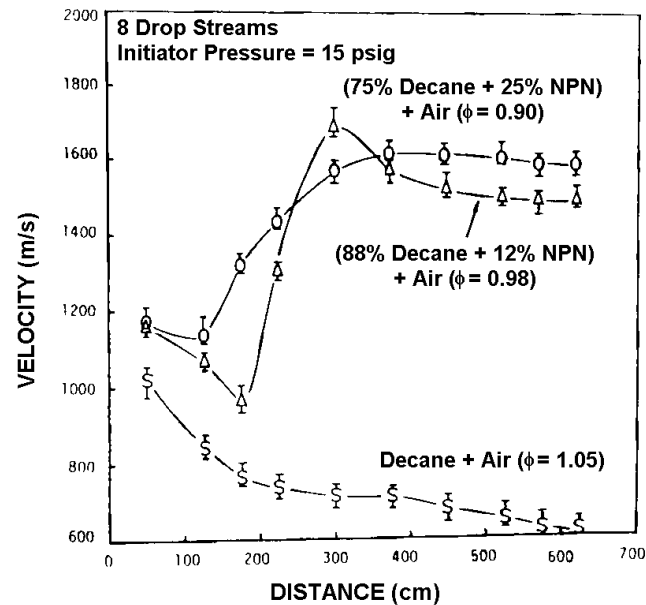
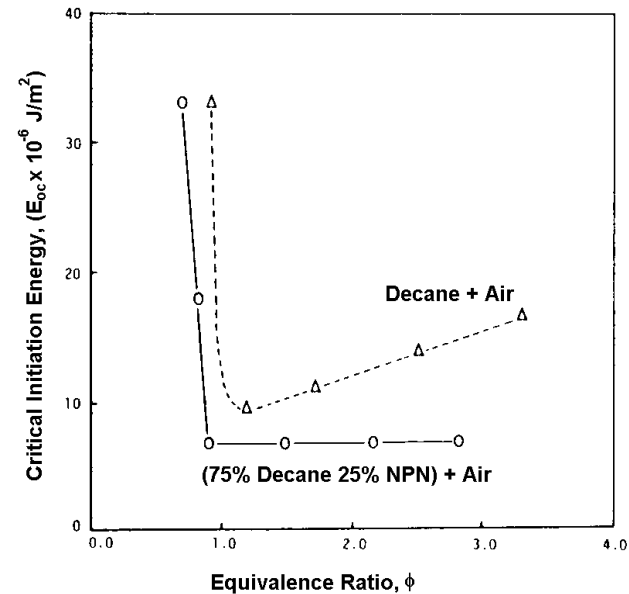
- **Task 1 - Build a simple parametric model of the PDE**
 - Estimate the possible performance benefits of additives which shorten DDT
 - Aid the interpretation of test data
 - Enable trade studies
 - Become familiar with the engine cycle
- **Task 2 – Conduct initiated PDE experiments at Stanford**
 - Gaseous fuels only
 - Transient pressure at six axial locations

Initiated Combustion

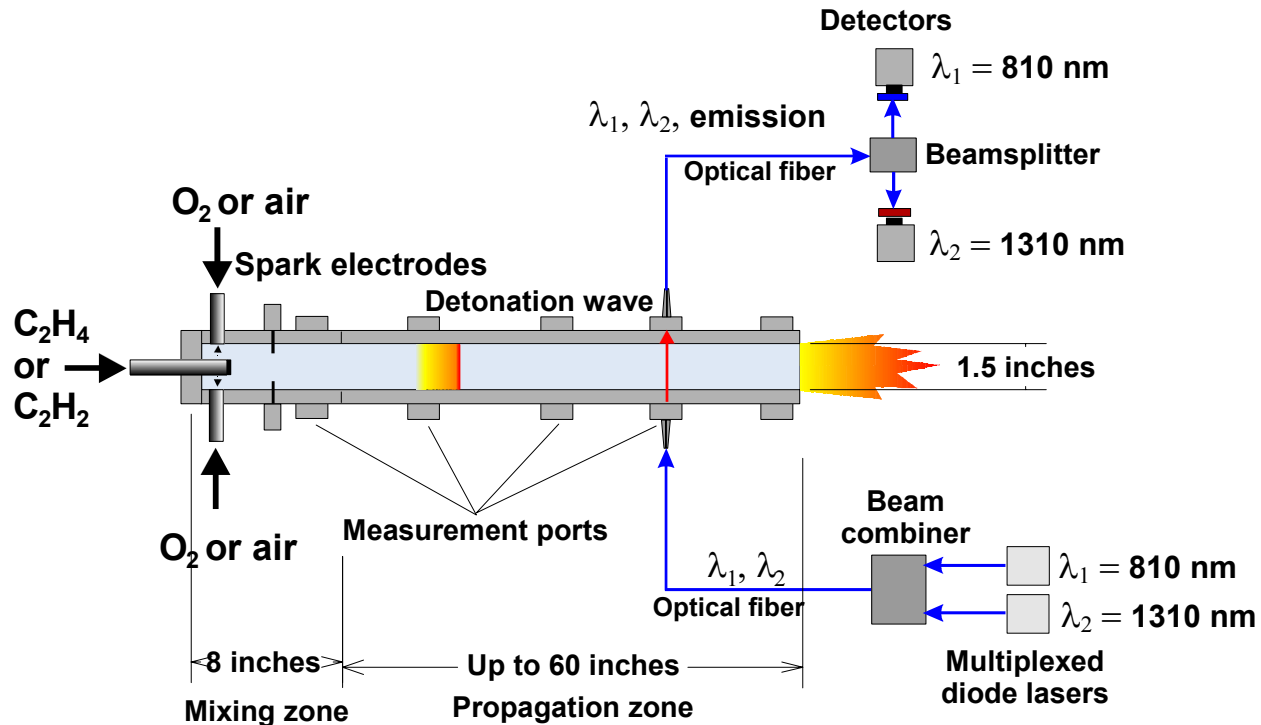


- **Initiator compounds have been observed to substantially shorten ignition delay and DDT**

Lin, Z.C., Nicholls, J.A., Tang, M.J., Kauffman, C.W., and Sichel, M., "Vapor Pressure and Sensitization Effects in Detonation of a Decane Spray," *Twentieth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh (1984).



Stanford Single Tube PDE



- High-speed pressure transducers at multiple axial locations
- Gaseous fuels only
- Low velocity initial mixture (<1 m/sec)

Fuels and Additives Studied

- **Fuels:**

- Ethylene (C_2H_4)
- Propane (C_3H_8) w/ N_2 Pressurant
- *n*-Butane (C_4H_{10}) w/ N_2 Pressurant

- **Additives:**

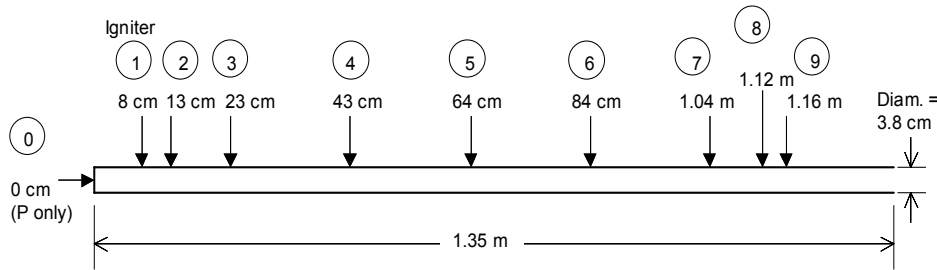
- Dimethyl Ether ($(CH_3)_2O$)
- Isopropyl Nitrate ($C_3H_7NO_3$)
- Diethyl Ether ($(C_2H_5)_2O$)
- Nitrous Oxide (N_2O)

- **Oxidizers**

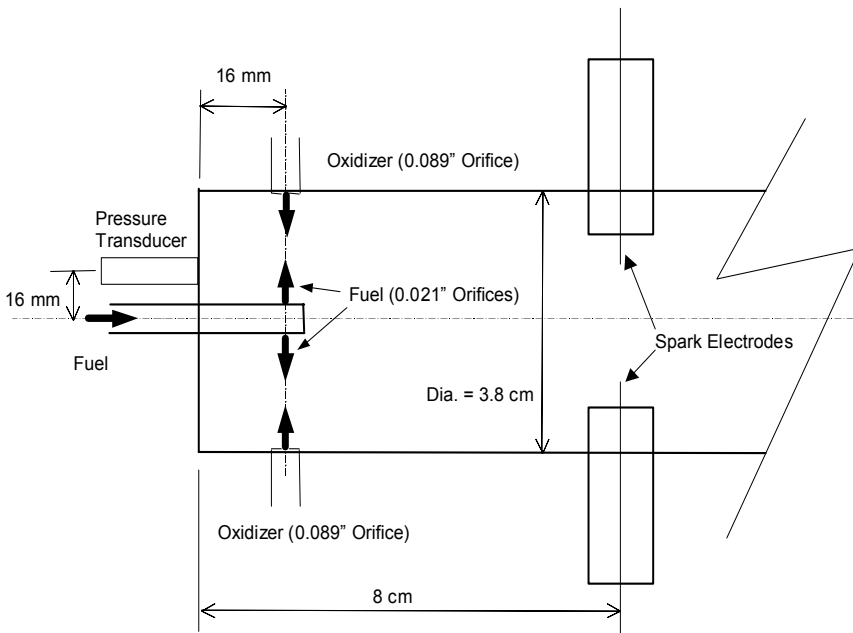
- O_2
- Air

Mixing/Injection Configuration #1

Measurement Locations in the Stanford PDE



Overall view



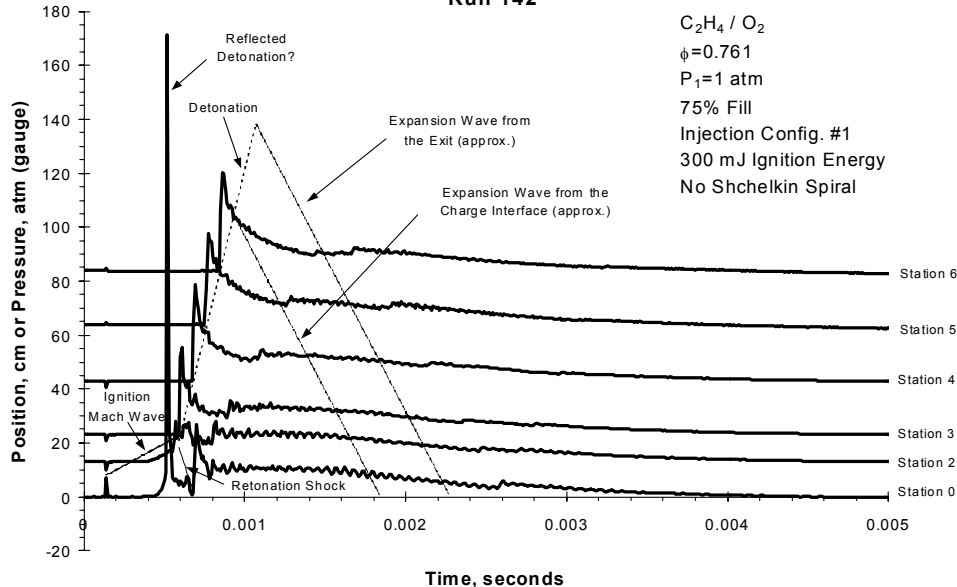
Close up of head end

- **Opposed jet fuel and oxidizer injection scheme**
- **Flow calibration accomplished by measuring the transient pressure rise with a closed combustor and choked flow**
- **Fuel and oxidizer orifices calibrated separately**

PDE Transient Pressures

Run 142

C_2H_4 / O_2
 $\phi=0.761$
 $P_1=1$ atm
75% Fill
Injection Config. #1
300 mJ Ignition Energy
No Shchelkin Spiral



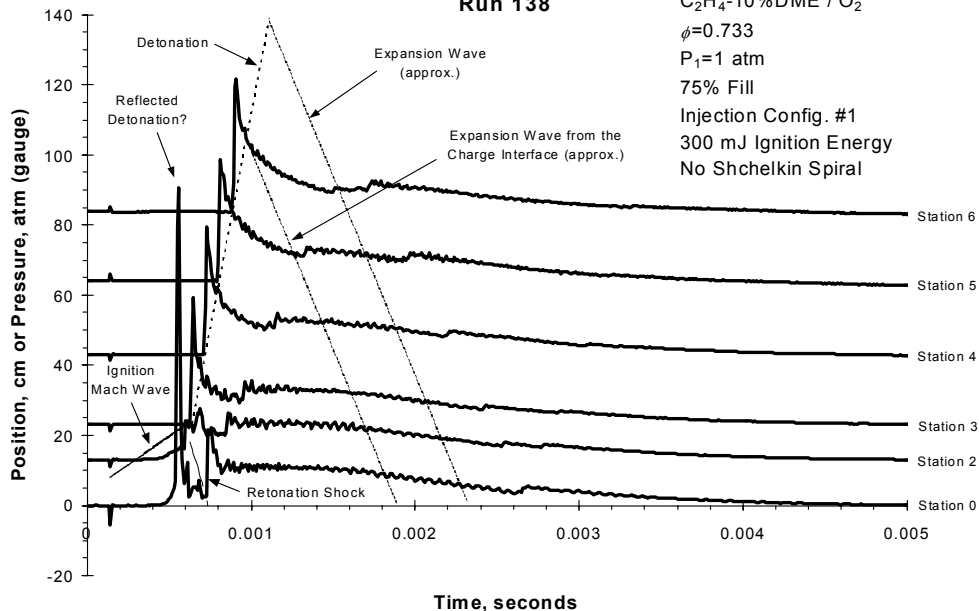
- Ethylene / O_2 mixture is very energetic

- short DDT time and distance
- reflected detonation at the head end

PDE Transient Pressures

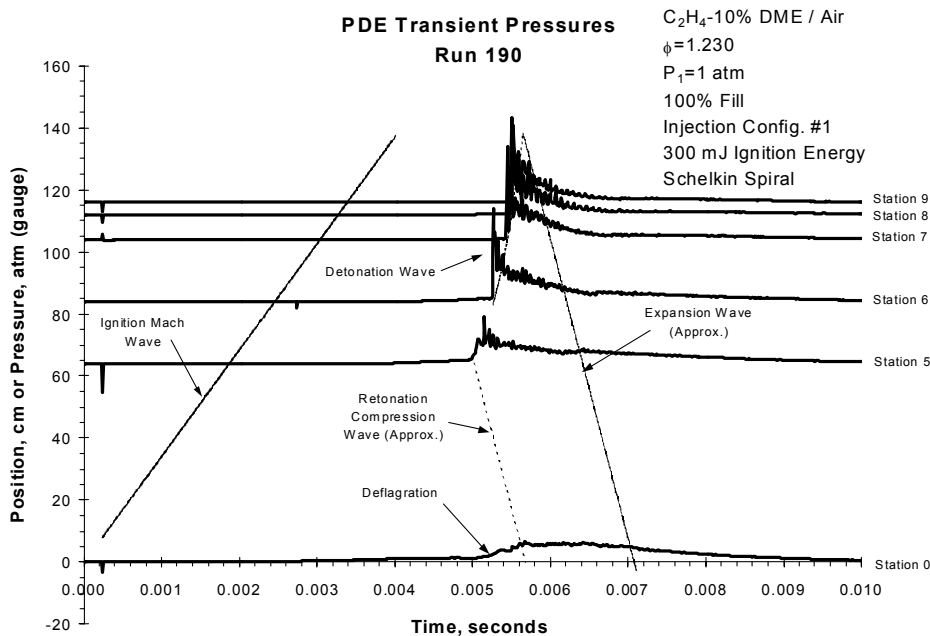
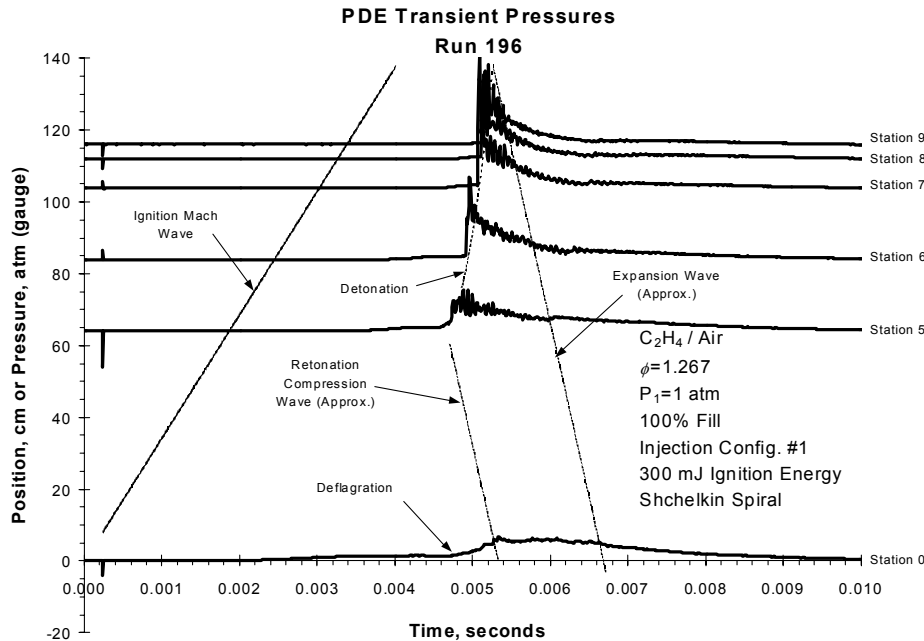
Run 138

C_2H_4 -10%DME / O_2
 $\phi=0.733$
 $P_1=1$ atm
75% Fill
Injection Config. #1
300 mJ Ignition Energy
No Shchelkin Spiral



- Addition of DME lengthens the DDT time

- Shchelkin spiral not required to obtain a detonation



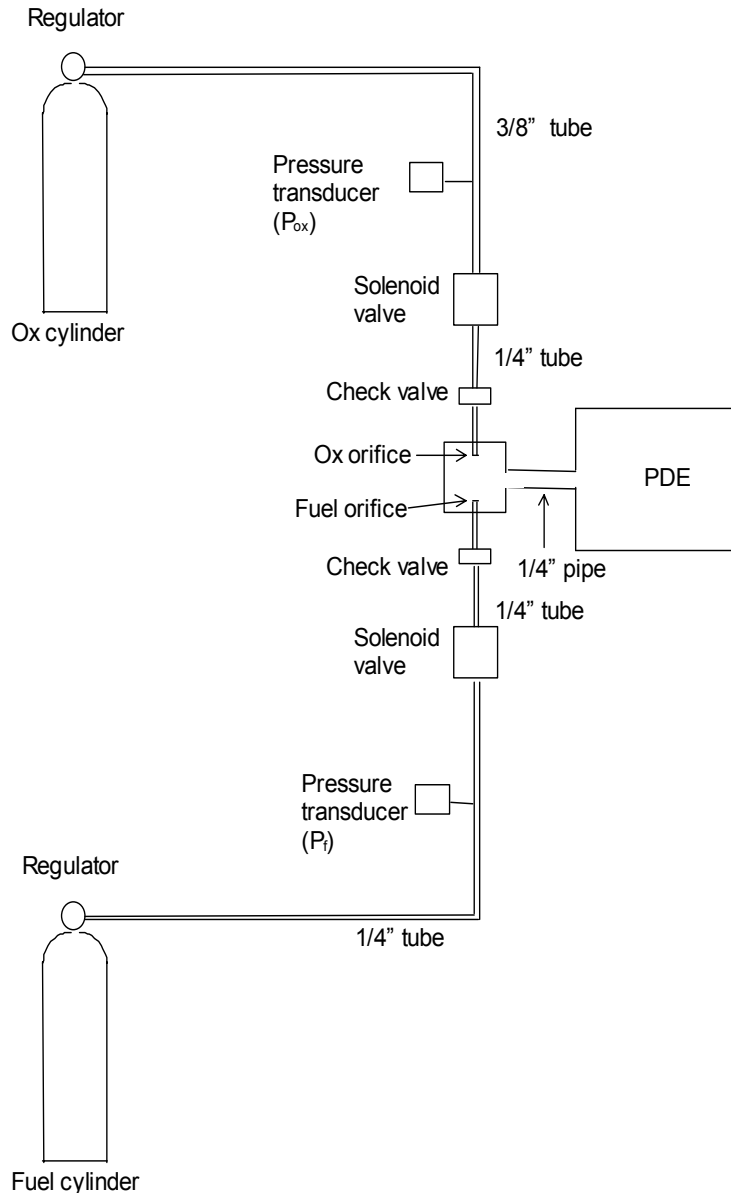
- **Ethylene / air mixtures are much less energetic**

- Long DDT times and distances
- Arrival of Mach wave at the exit before the detonation wave

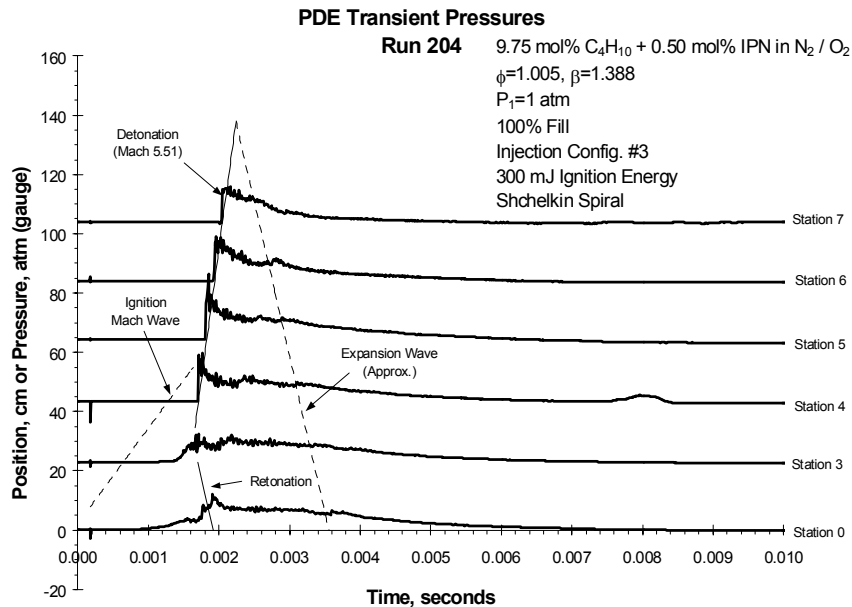
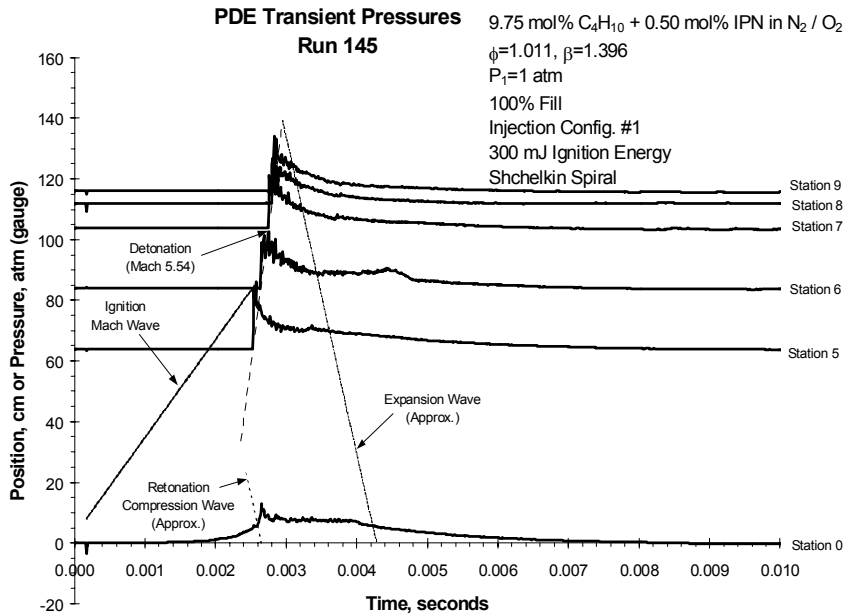
- **Addition of DME lengthens the DDT time**

- **Shchelkin spiral required to achieve detonation**

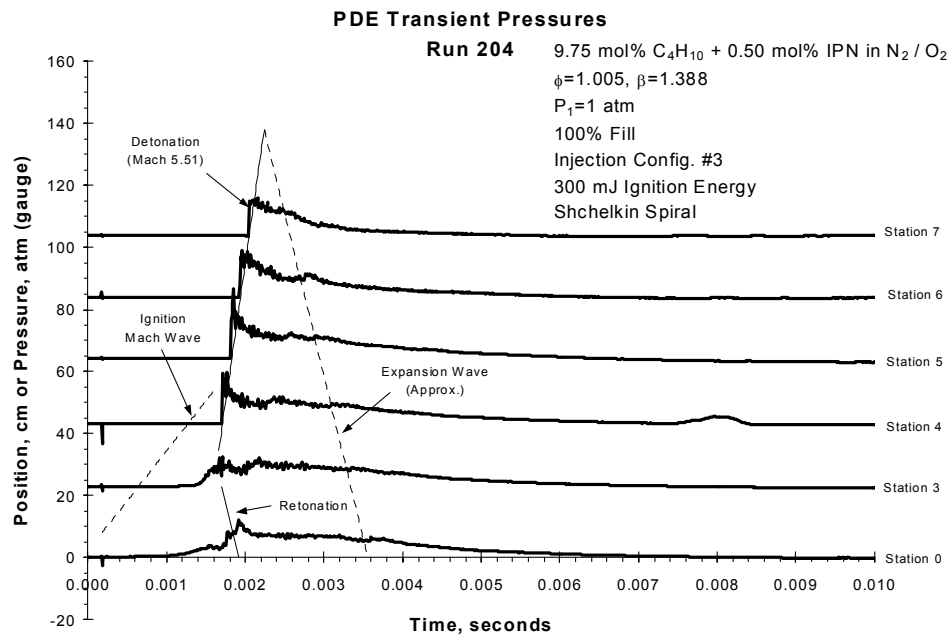
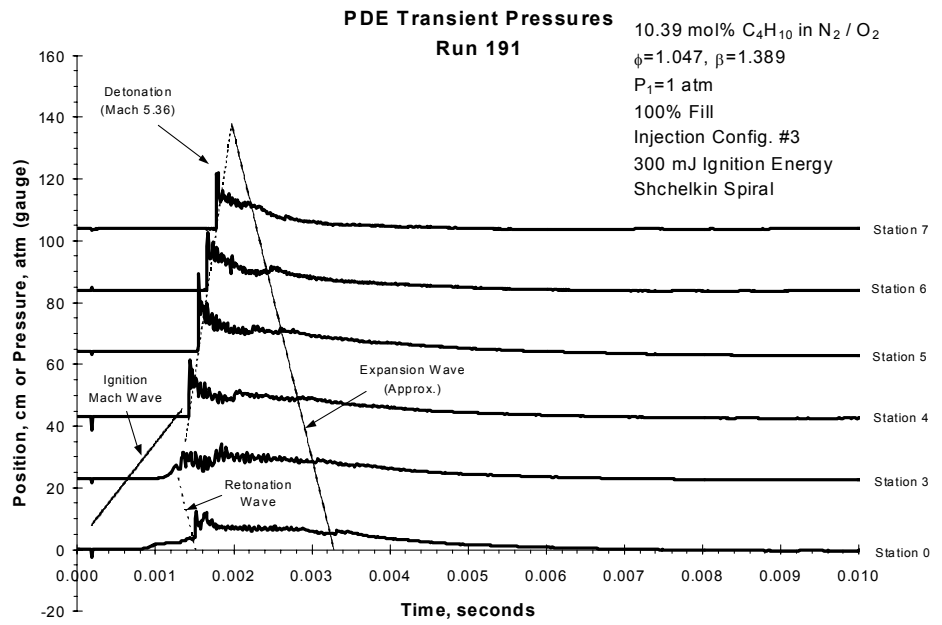
Mixing/Injection Configuration #3



- Initial results with butane in Mixing Config. #1 appeared suspicious
- Opposed jets are prone to the formation of stable coherent structures with low mixing rates
- Poor mixing could explain the lack of additive effects
- Revised the fuel injection and mixing configuration
 - Shortened DDT
 - Improved metering confidence



- Improved mixing obtained with **Config. #3**
 - 40% decrease in DDT distance
 - 53% decrease in DDT time
- Confirmed that additives generally increased DDT time and distance



- **Negative *n*-Butane response to isopropyl nitrate indicates that autoignition is not a dominant mechanism in DDT**

Laminar Flame Speed

$$S_L \propto \sqrt{\alpha \times RR}$$

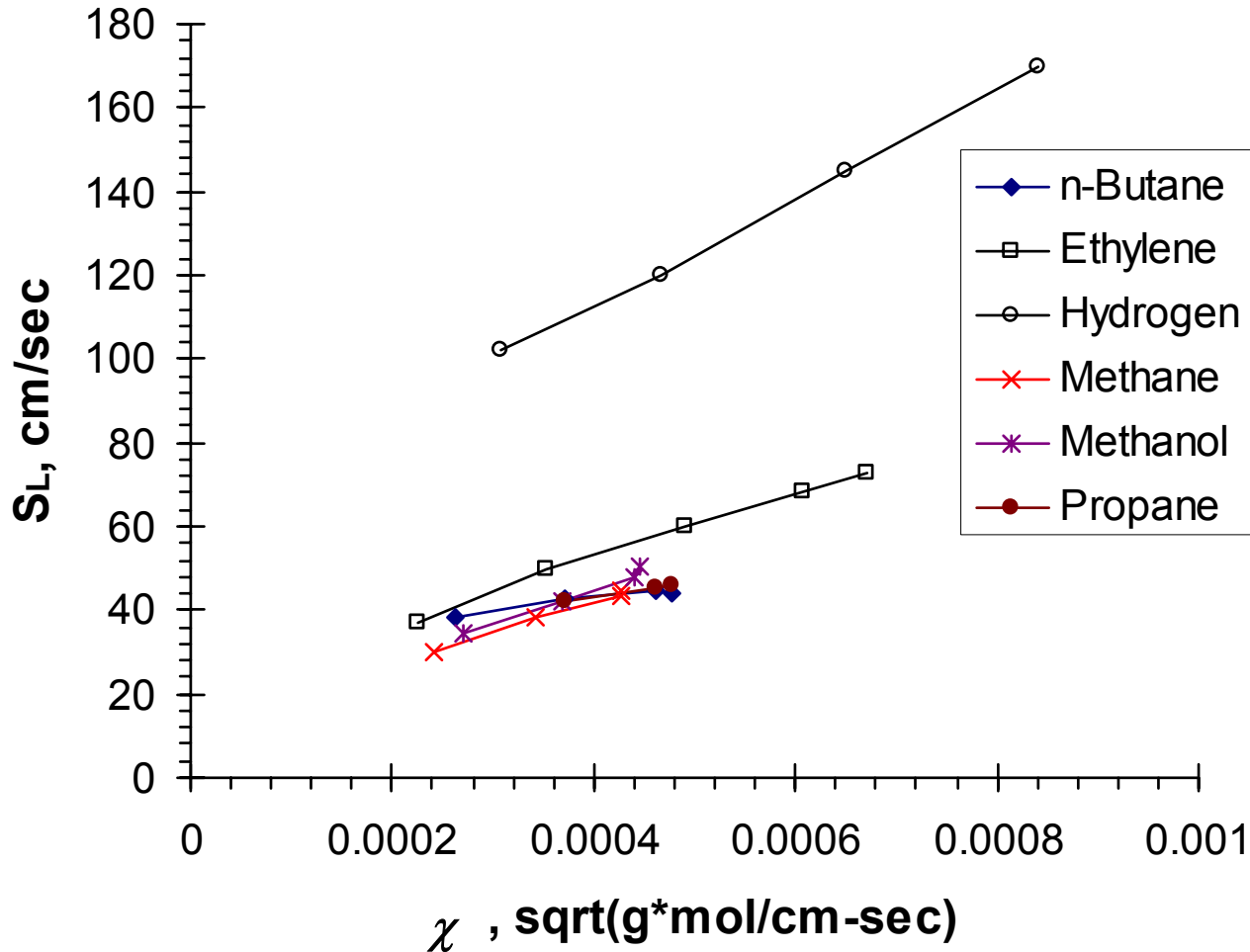
$$\chi = \sqrt{\alpha_{th} [M] (6.5 X_{H,eq} + X_{OH,eq} + X_{O,eq})}$$

$$[M] = \frac{P}{R_u T_f}$$

- **Thermal (e.g. Mallard and LeChatelier) and chain-carrier (e.g. Tanford-Pease) theories of flame propagation both indicate that the laminar flame speed depends on the diffusivity \times reaction rate**
- **Combining these theories yields the parameter χ based on equilibrium burned gas properties**

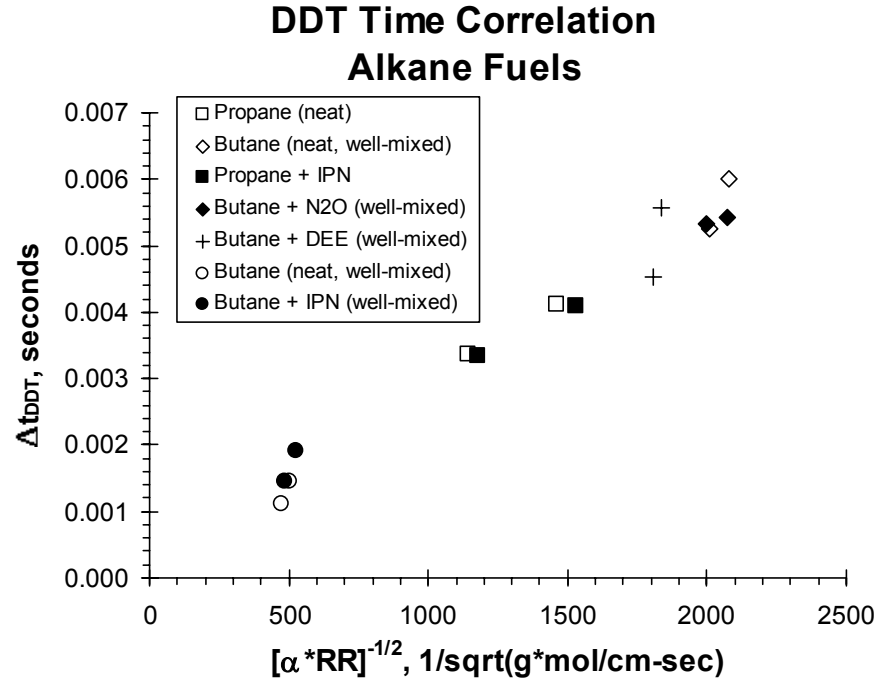
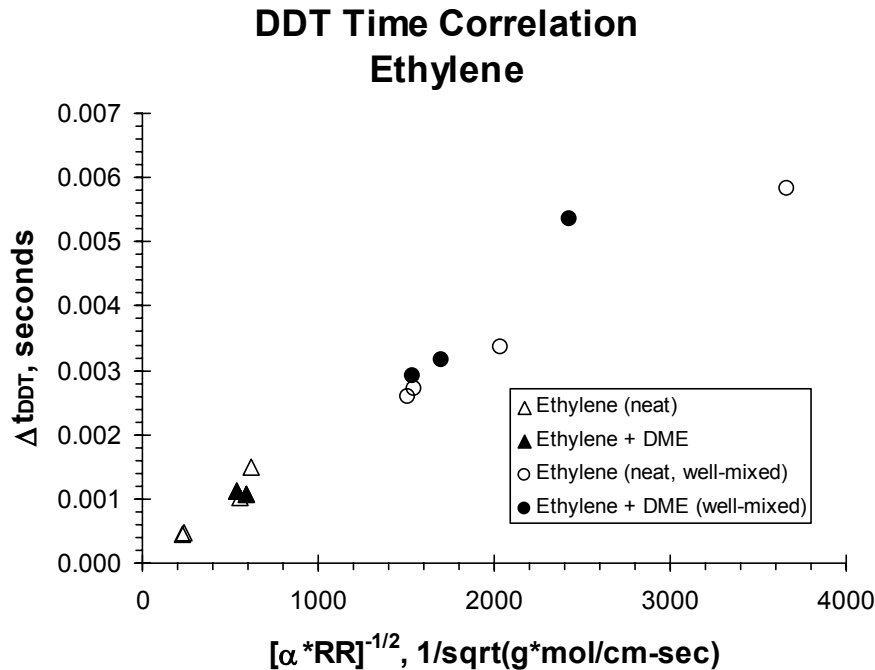
Laminar Flame Speed Correlation

Laminar Flame Speeds



Fuel/Air Mixtures
 $0.7 < \phi < 1.1$
25 C

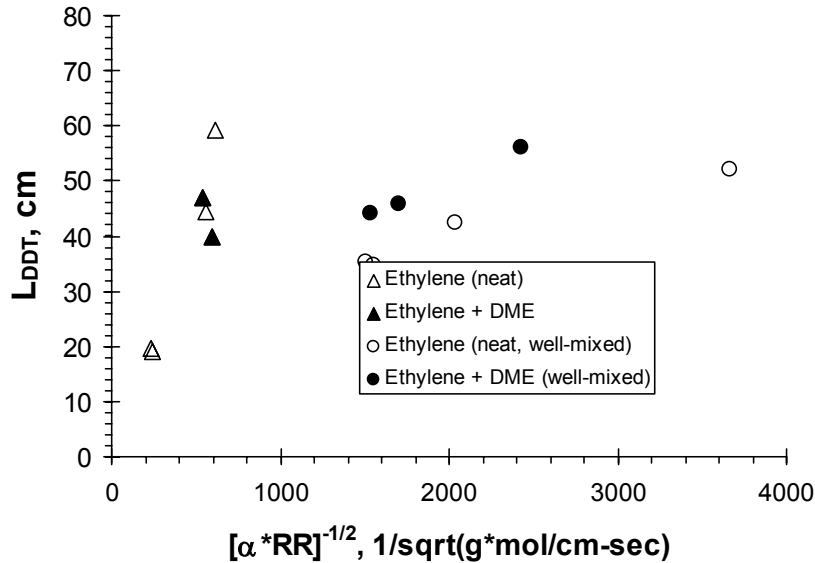
Indications of DDT Time Dependence on Laminar Flame Speed



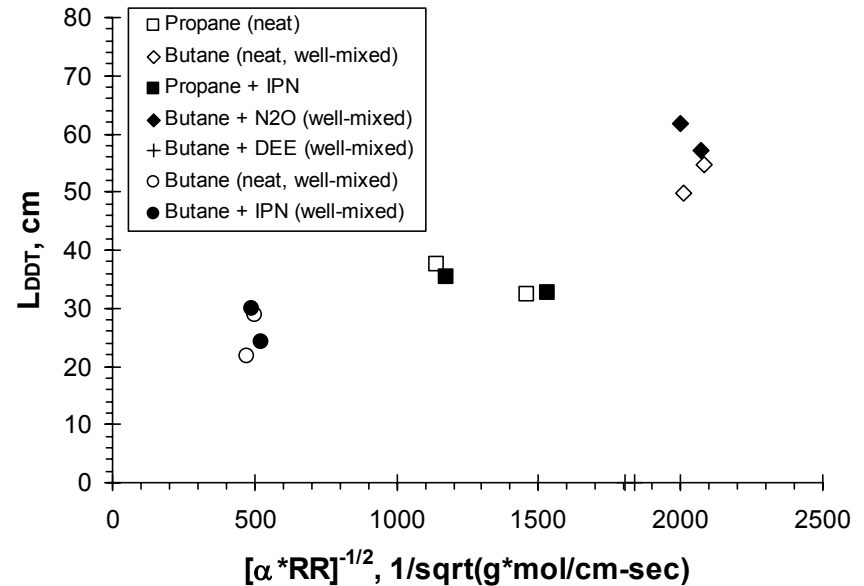
- Excellent correlation between DDT times and $1/\chi$ across a wide range of β (N_2/O_2 ratio)
- Oxygenate species like initiator compounds lower the flame temperature & flame speed

DDT Distance Dependence on Laminar Flame Speed

DDT Length Correlation
Ethylene



DDT Length Correlation
Alkane Fuels



- Some indication of dependence of DDT distance on $1/\chi$

Conclusions

- **Experimental results indicate that DDT is not improved by compounds known to decrease ignition delay times**
- **Mixing has a larger impact on DDT**
- **Improvements observed previously by Lin in *n*-decane spray DDT were probably due to the relatively high volatility of propyl nitrate (23.5 torr versus 1.5 torr for *n*-decane at 25 C)**
- **DDT times correlate well with a parameter describing the mixture laminar flame speed**
- **Predetonator probably required for an air-breathing PDE**