COMBUSTION CHARACTERIZATION AND MODELLING OF FUEL BLENDS FOR POWER GENERATION GAS TURBINES

University of Central Florida

Eric L. Petersen

SCIES Project 04-01-SR114

DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

Tom J. George, Program Manager, DOE/NETL

Richard Wenglarz, Manager of Research, SCIES

Project Awarded (05/01/2004, 36-Month Duration)

$556,937 Total Contract Value ($405,990 DOE)

Gas Turbine Need

Fuel Composition Variation *is a Concern*

Natural Gas:

CH_4 + C_2H_6 + C_3H_8 + … } $94\% < CH_4 < 99\%$

Exotic Fuel Blends:

CH_4 + H_2 + C_2H_6 + C_3H_8 + C_4H_x + C_5H_x } **$40\% < CH_4 < 99\%$**

Syngas:

H_2 :	9 – 45%
CO:	20 – 55%
H_2O:	0 – 40%

Fuel Variation Impacts
Chemistry
&
Engine Performance !

Gas Dynamics Laboratory
University of Central Florida

Project Objectives

There are Several Major Objectives…

1. Measure **Ignition Delay Times** of Fuel Blends at Engine Pressures
2. Develop Efficient **Test Matrices** to Cover Wide Range of Blends
3. Identify Appropriate Chemical **Kinetics Mechanisms**
4. Assemble **Reduced Kinetics** Mechanism(s) for CFD
5. Apply **Reacting-Flow CFD** Model to Explore Fuel Flex Issues
6. Measure **Flame Speeds** for Varying Fuel Blends
7. Acquire **Detailed Kinetics Data** for Model Improvement

Gas Dynamics Laboratory
University of Central Florida

Approach

Project is Divided into 7 Tasks

Task 1 – Test Matrix and Literature Search (Yr 1)

Task 2 – Autoignition Measurements (Yr 1, 2, 3)

Task 3 – Flame Speed Measurements (Yr 2, 3)

Task 4 – Chemical Kinetics Modeling (Yr 1, 2, 3)

Task 5 – CFD Modeling Effort (Yr 1, 2, 3)

Task 6 – NOx Measurements (Yr 3)

Task 7 – Mechanism Validation Measurements (Yr 2, 3)

Results

We Have Had ***Several Major Results*** *the 1st 17 Months*

- **Ignition Times for Several Binary CH_4 Blends (ϕ = 0.5) Measured**
  - H_2, C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}
  - 1100 – 1500 K, 1 – 25 atm
- **Autoignition and Other Test Matrices Developed**
- **Ignition Delay Times of Several CO/H_2 Blends (ϕ = 0.5) Measured**
- **Preburner Autoignition Study Completed**
- **Gas Turbine CFD Model Identified and Tested**
- **Flame Speed Rig Designed**
- **Detailed Kinetics Measurements for Syngas Mixtures Performed**

Background and Experimental Setup

Background

Ignition Times *Are Important for Two Reasons:*

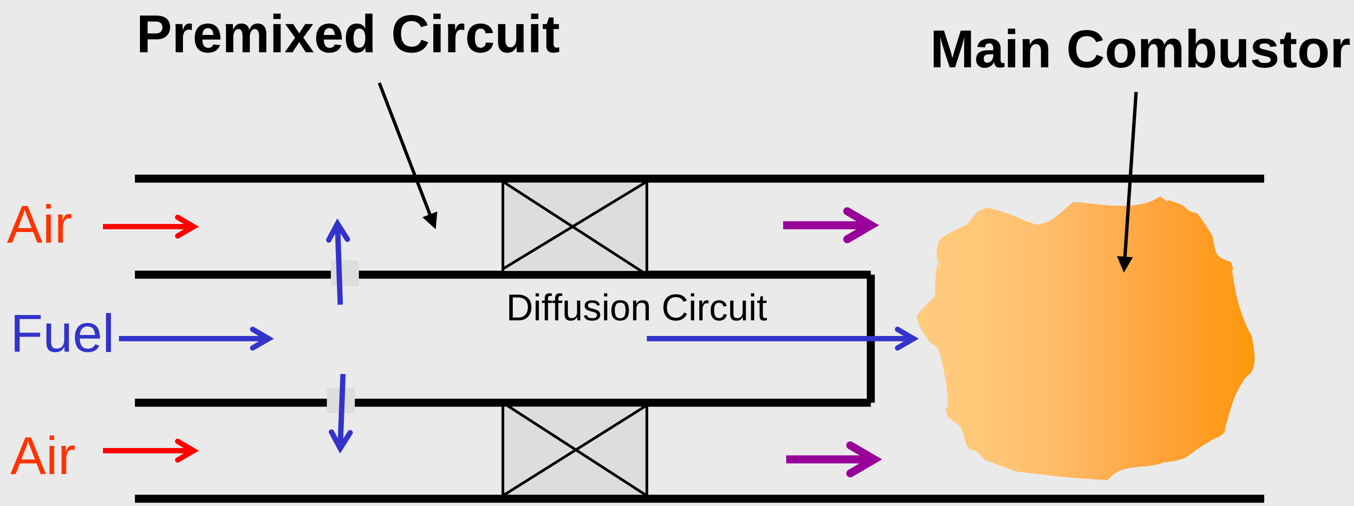
1. **Autoignition** of Premixed Fuel/Air Mixtures

2. **Characteristic Times** for Calibrating Chemical Kinetics

Gas Dynamics Laboratory
University of Central Florida

Background

Autoignition *for Premixer and* ***Characteristic Times*** *for Burner*



600 – 800 K
10 – 25 atm
~ 10 ms

Autoignition?

1300 – 1900 K
10 – 25 atm

- **Chemical Kinetics**
- **Flame Speed**
- **Stability**

Gas Dynamics Laboratory
University of Central Florida

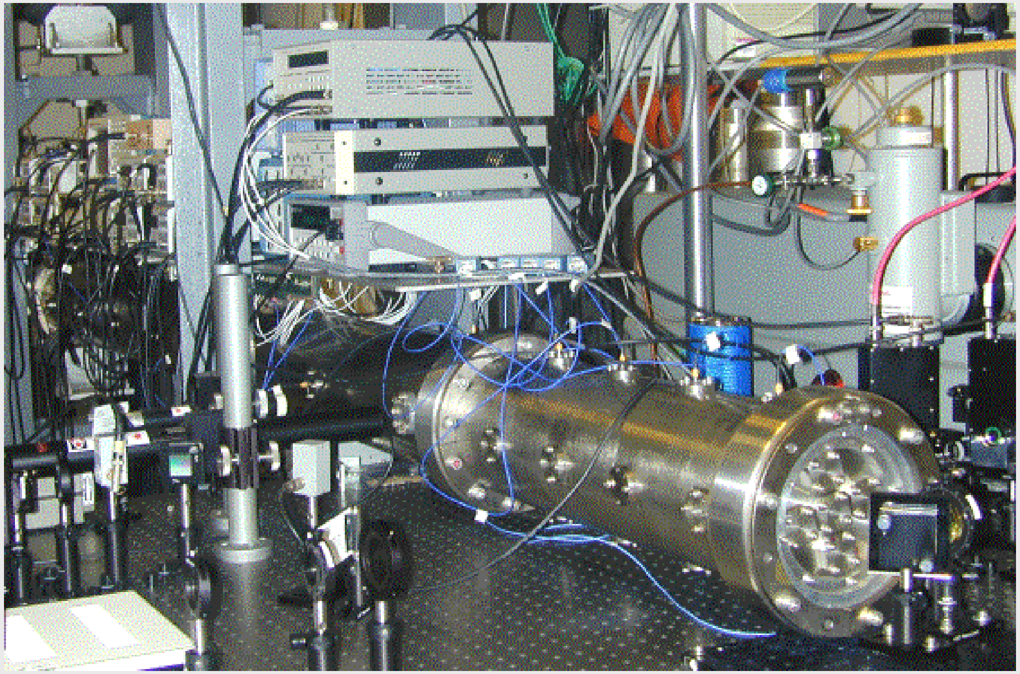
Experiment

Shock-Tube Facility is Capable of ***Elevated Pressures***

Specifications

- Driver: 7.6 cm Dia, 3.5 m
- Driven: 16.2 cm Dia, 10.7 m
- Digital DAQ (5 MHz, 12 bit)
- Optical Diagnostics
- Pressure (1 – 100 atm)

Aerospace Shock Tube Facility

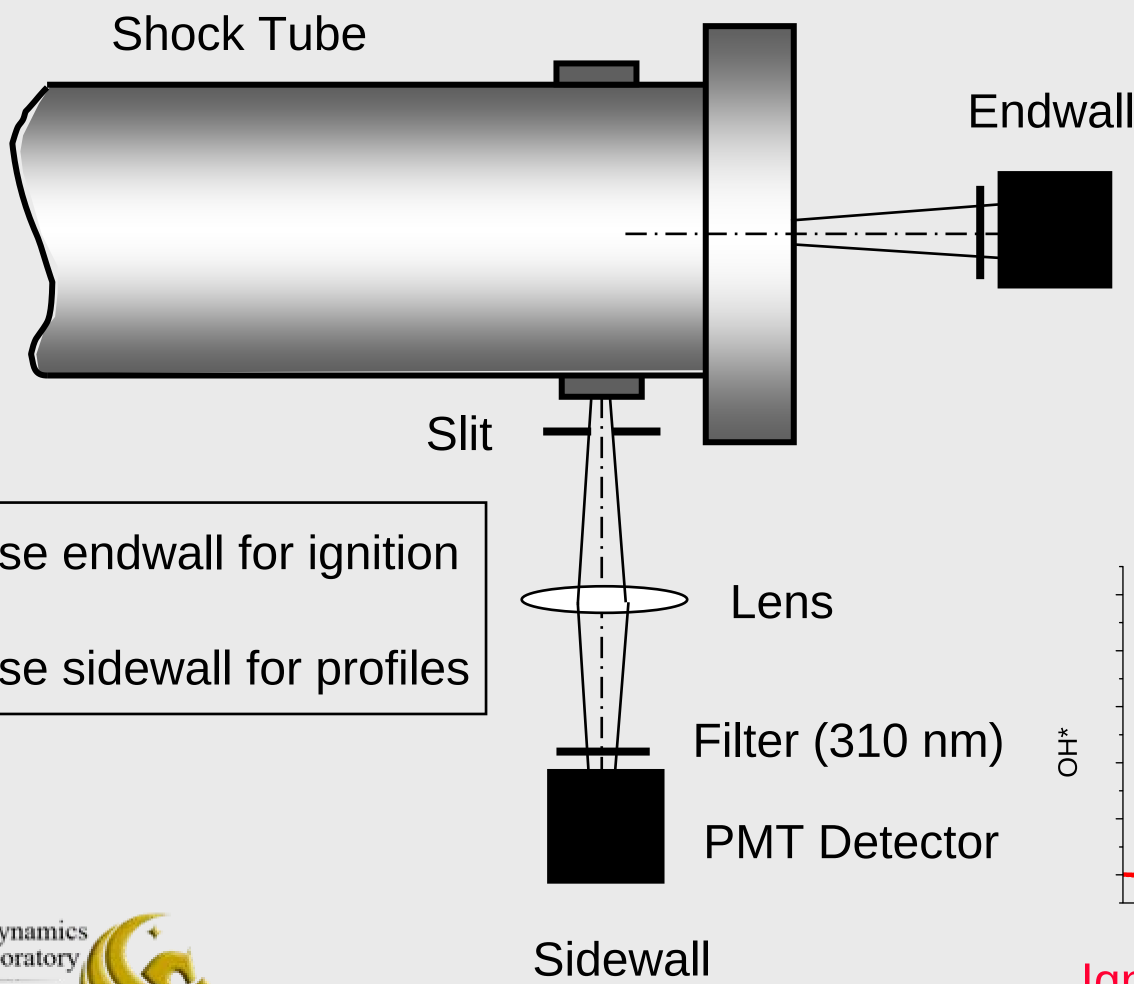


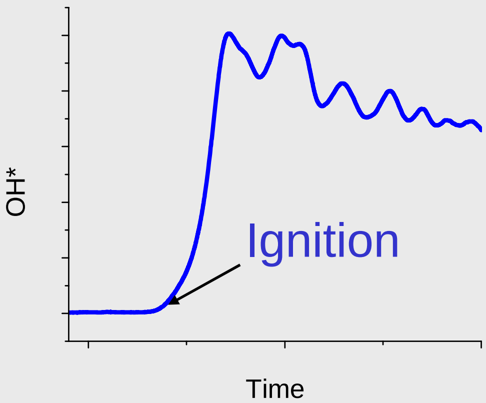
Gas Dynamics Laboratory University of Central Florida

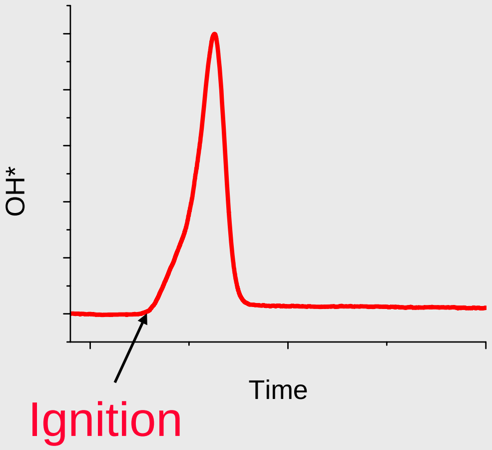
THE AEROSPACE CORPORATION

Experiments

Chemiluminescence (OH* or CH*) *Detected at Endwall and Sidewall*





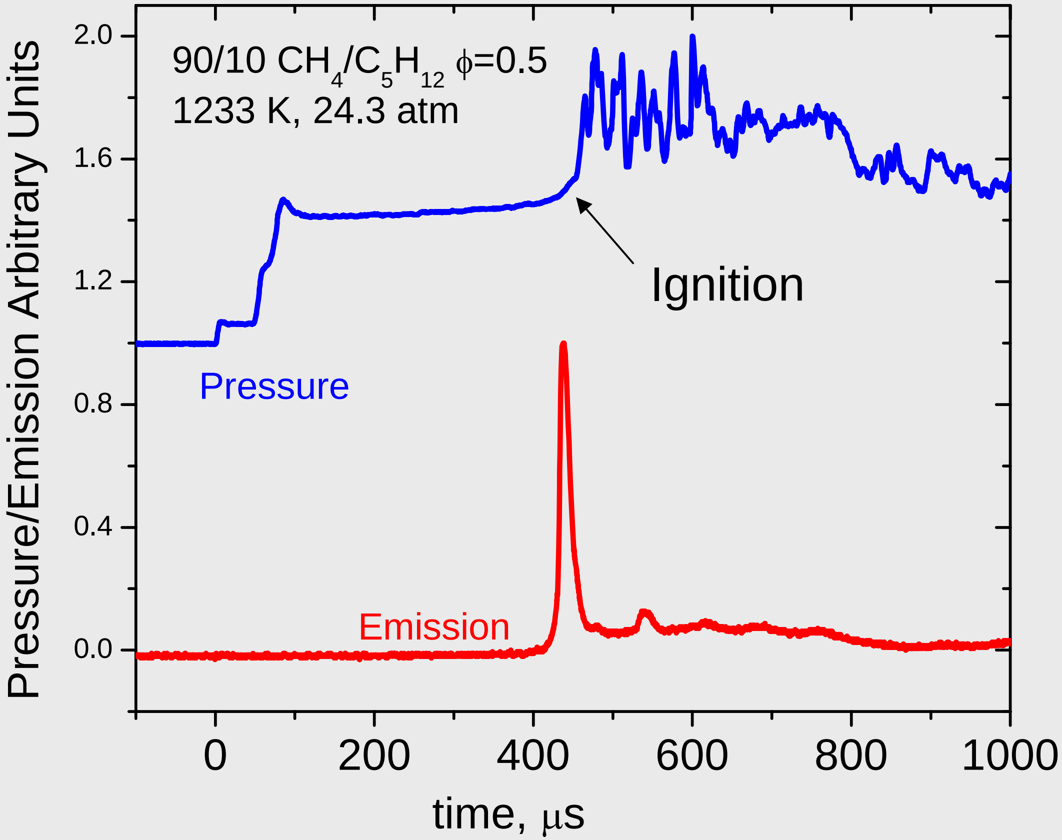


- Use endwall for ignition
- Use sidewall for profiles

Experiment

Sample ***Sidewall Emission and Pressure*** *Show Highly Exothermic Reaction*

Sidewall Data Traces



Technical Results

Task 2 – Ignition (CO/H_2)

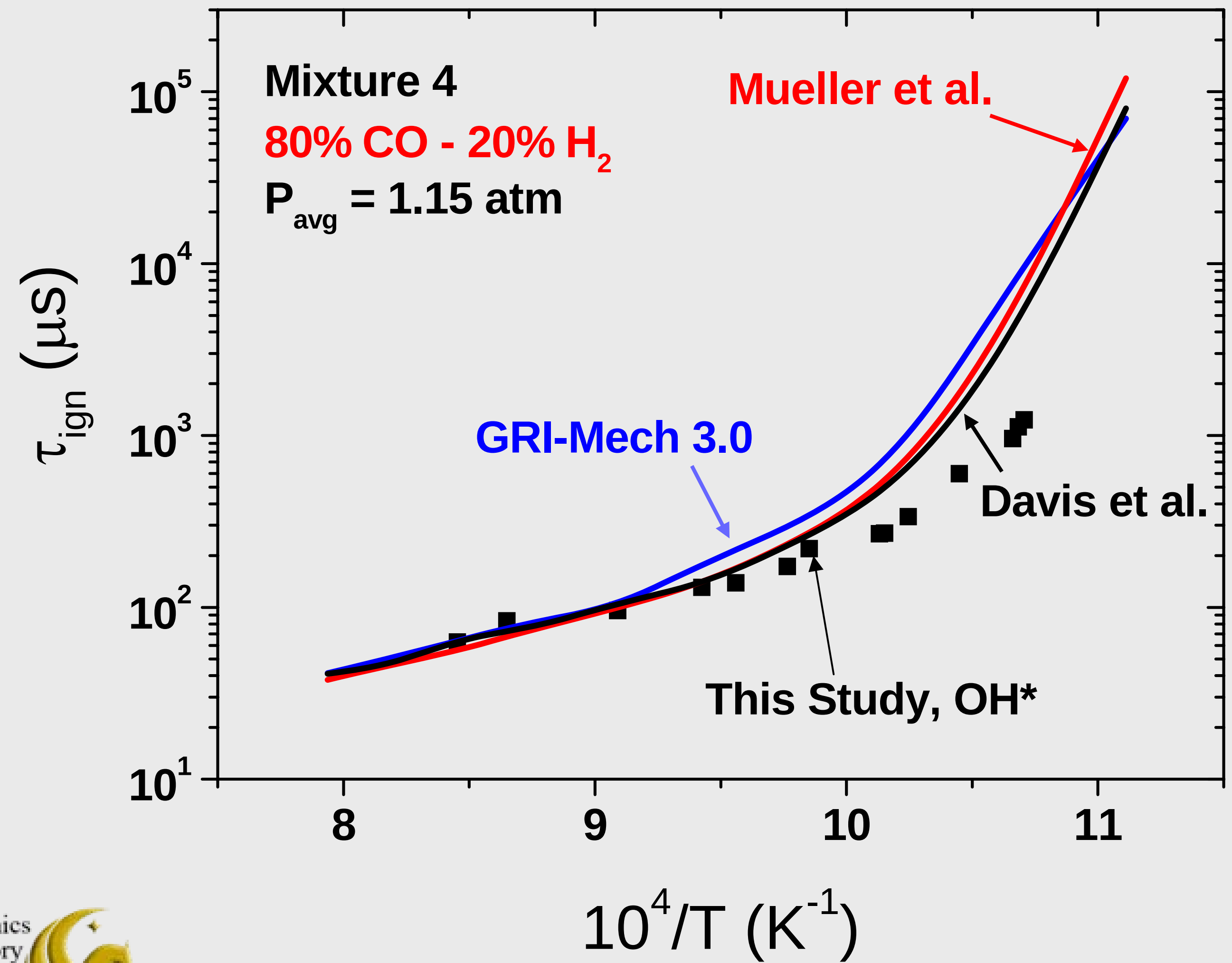
*Many **Syngas Blends** Have been Studied Over a Wide Range of Temperature and Pressure*

1. CO/H_2 Blends: from **95% CO** to **5% CO**
2. T = **890 – 1300 K**
3. P = **1 - 15 atm**
4. Fuel-Lean: **ϕ = 0.5**
5. Comparison with Kinetics Models

Gas Dynamics Laboratory
University of Central Florida

Task 2 – Ignition (CO/H_2)

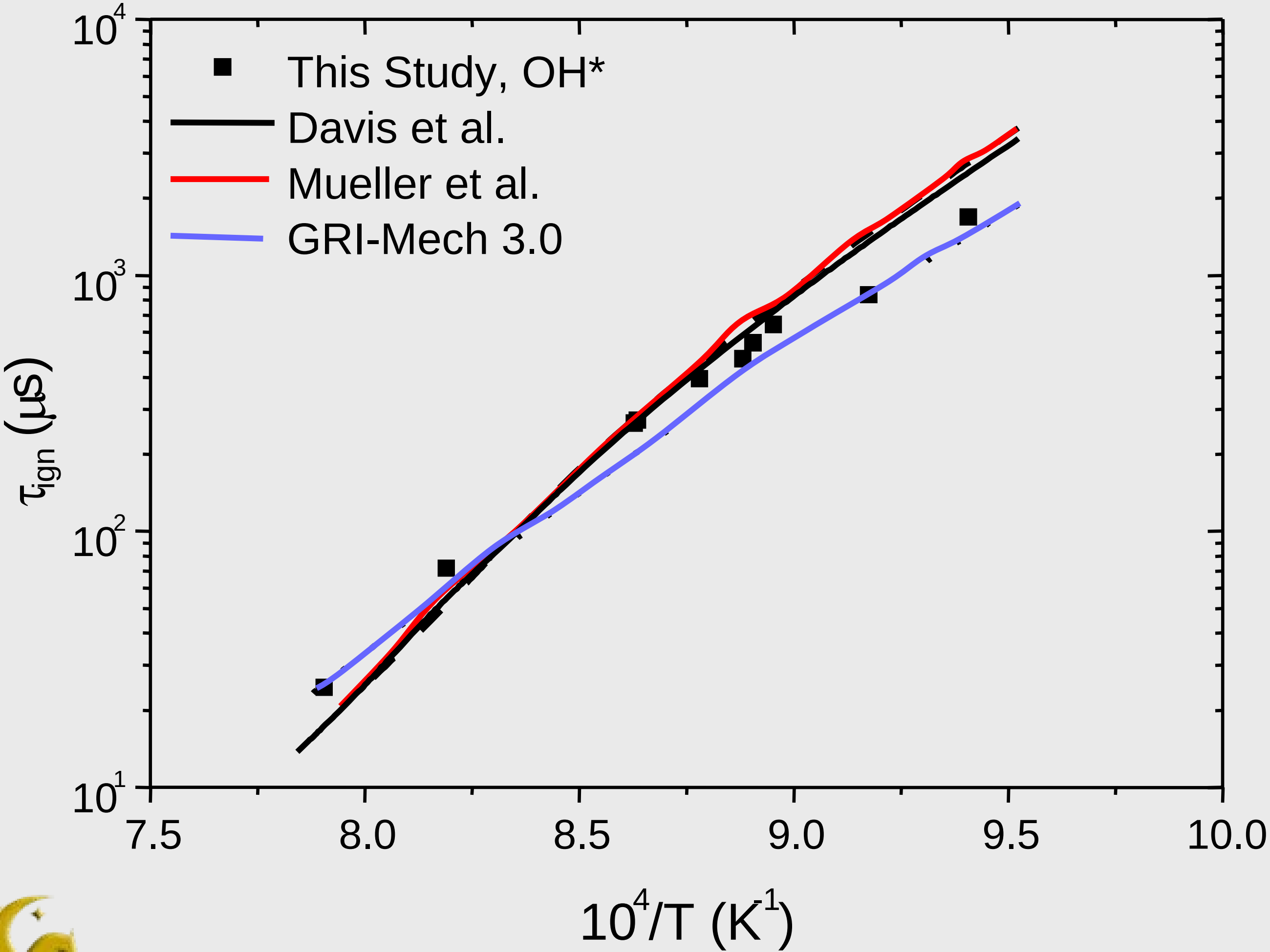
Kinetics Models Capture Basic Trends, Particularly at High T



- 80/20 CO/H_2
- $\phi = 0.5$

Task 2 – Ignition (CO/H_2)

Models Show Good Agreement at Highest Pressures



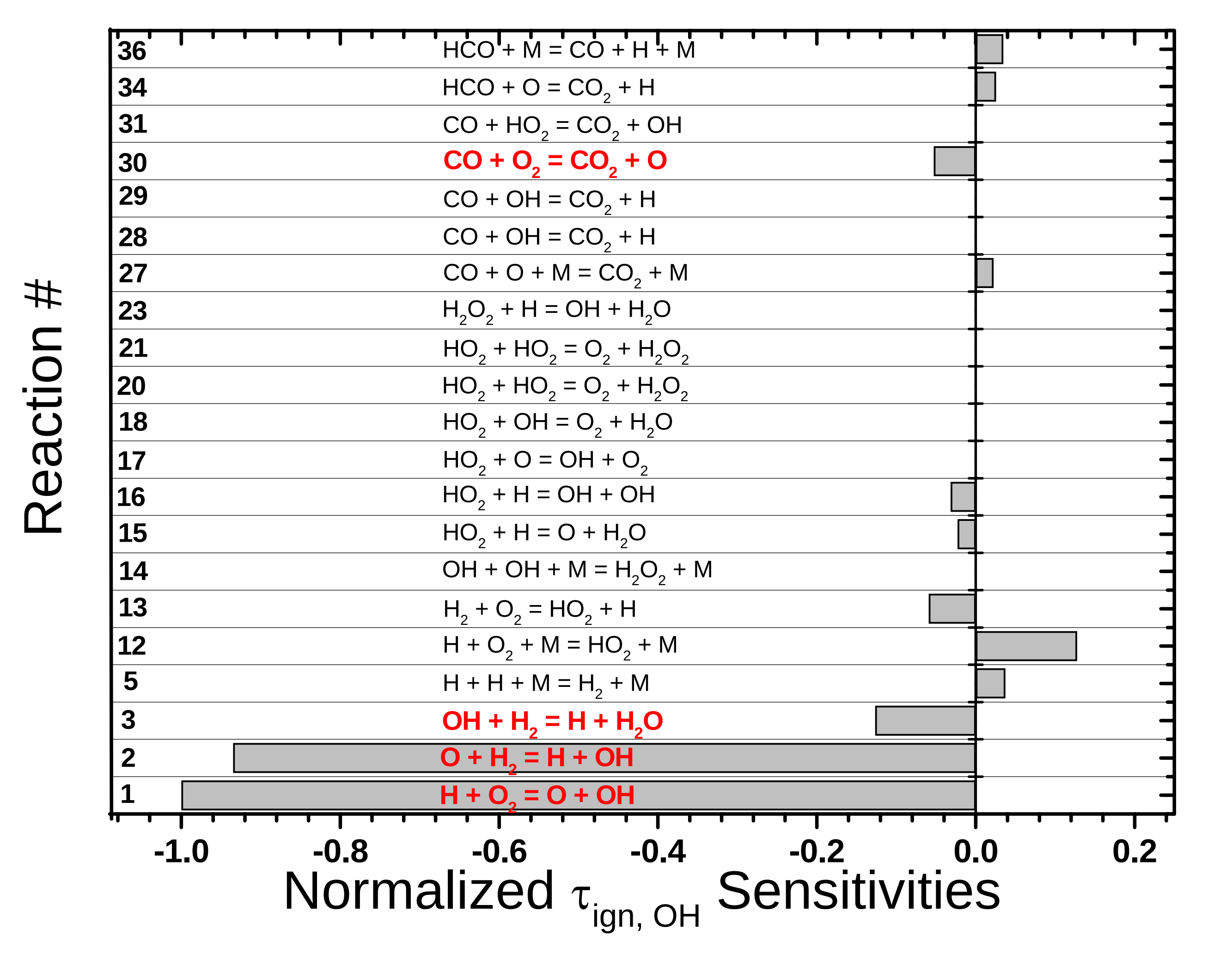
- **90/10 CO/H_2**
- **14.3 atm**

Task 2 – Ignition (CO/H_2)

Hydrogen Oxidation Kinetics Dominate Ignition at ***Higher Temp.***

95% CO – 5% H_2

T= 1250 K



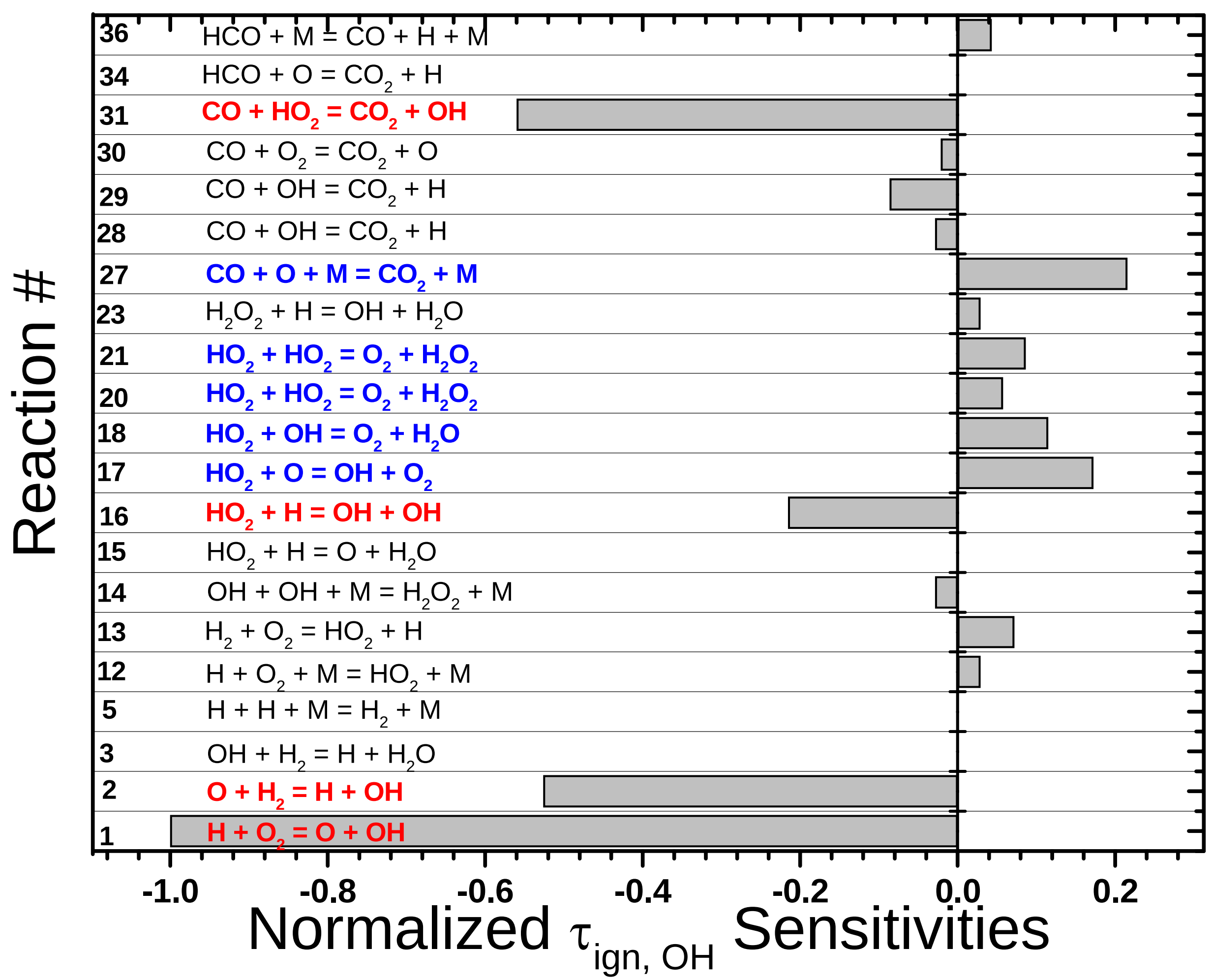
Gas Dynamics Laboratory
University of Central Florida

Task 2 – Ignition (CO/H_2)

Peroxide and CO Reactions Also Contribute at ***Lower Temp.***

95% CO – 5% H_2

T= 900 K



Gas Dynamics Laboratory
University of Central Florida

Task 2 – Ignition (CH_4/Other)

Several ***CH_4-Based Blends*** *Were Explored at Lean Conditions*

1. CH_4/Other Binary Blends
   - **H_2** (80/20, 60/40)
   - **C_2H_6** (90/10, 70/30)
   - **C_3H_8** (80/20, 60/40)
   - **C_4H_{10}** (90/10, 70/30)
   - **C_5H_{12}** (90/10, 70/30)

2. T = **1100 – 1500 K**

3. P = **1 - 25 atm**

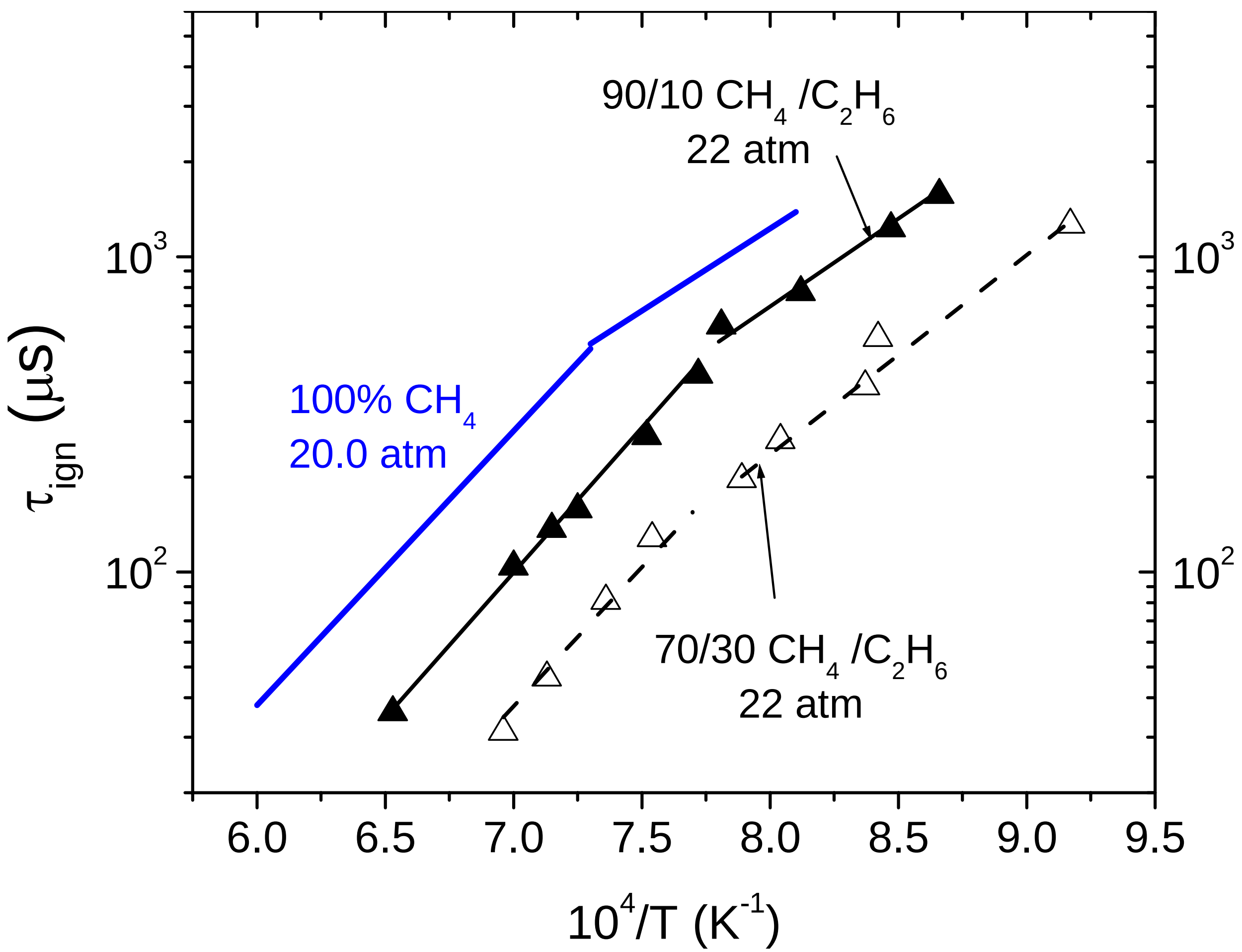
4. Fuel-Lean: **ϕ = 0.5**

Task 2 – Ignition (CH_4/Other)

*All Blends **Accelerated Methane Ignition** over Range Studied*

CH_4 – C_2H_6

ϕ = 0.5

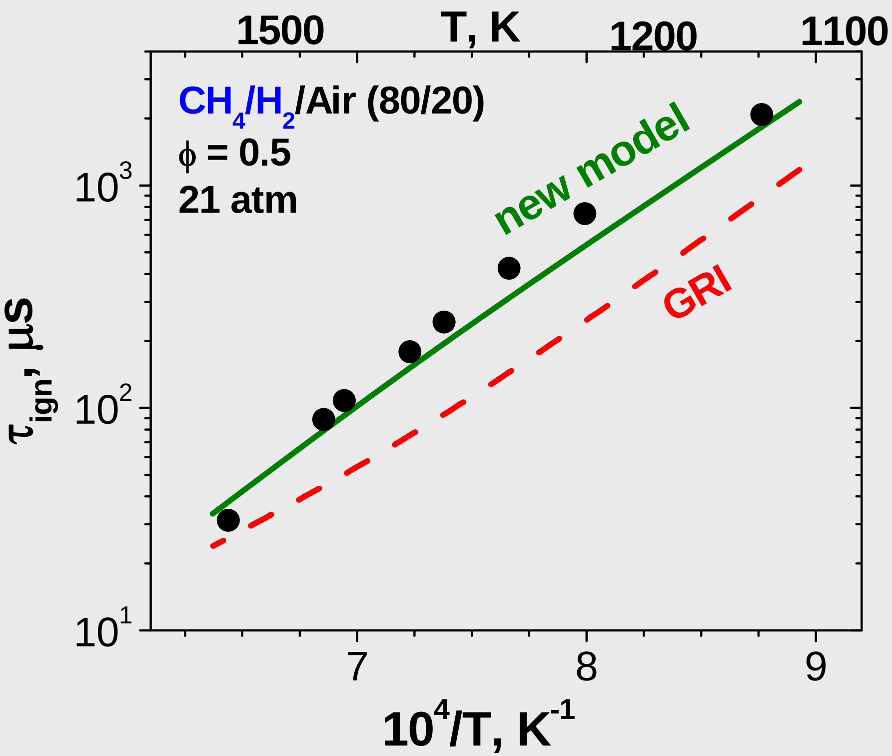


Gas Dynamics Laboratory
University of Central Florida

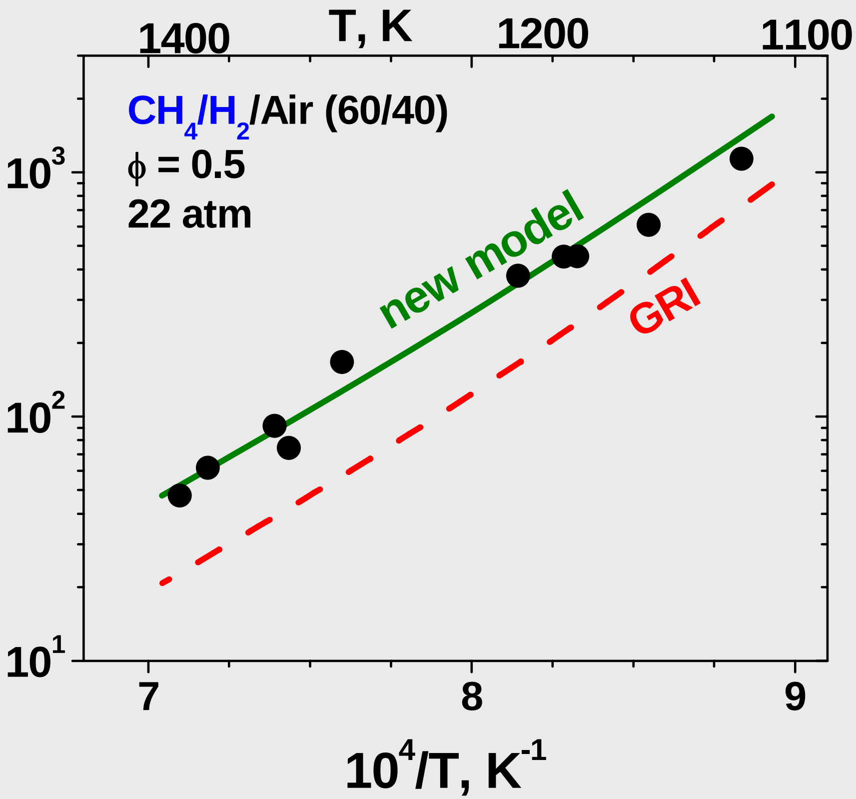
Task 2 – Ignition (CH_4/Other)

***Improved Mechanism** for CH_4+H_2 at Elevated P Developed*

80/20



60/40



Gas Dynamics Laboratory
University of Central Florida

Task 2 – Autoignition

A Separate Study was Conducted to Gauge ***Autoignition Tendency*** *of a Wide Range of CH_4-HC Blends*

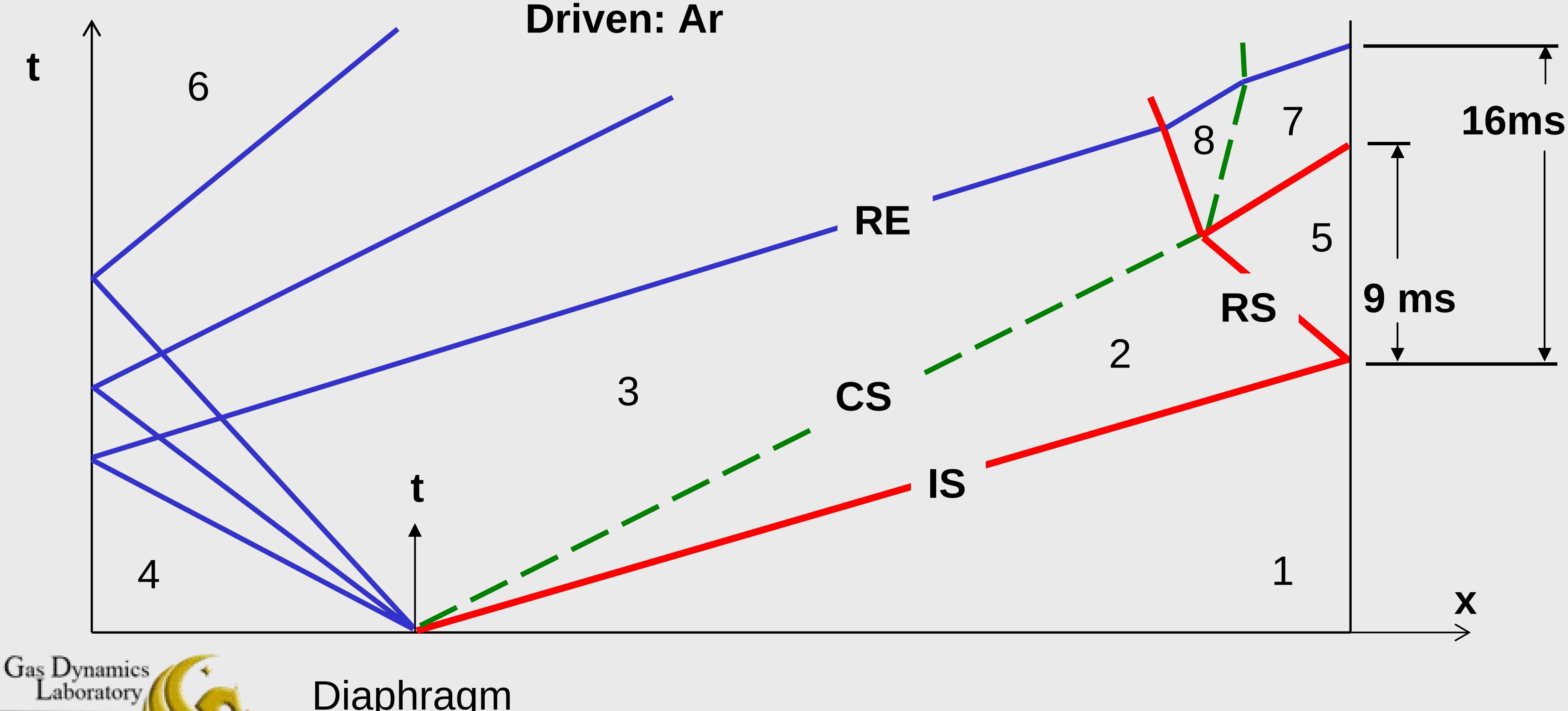
1. Fuel-Lean Mixtures: **ϕ = 0.5**
2. T = **800 K** (Upper Limit of Burner Inlet)
3. P = **18 atm**
4. $CH_4 + C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}, H_2$
5. Will the Mixture Ignite within **10 ms**?

Gas Dynamics Laboratory
University of Central Florida

Task 2 – Autoignition

Model Predicts ***16-ms Test Time*** *at 1000 K for He-C_3H_8 Driver*

T_5 = 1000 K
Driver: 55% He + 45% C_3H_8
Driven: Ar



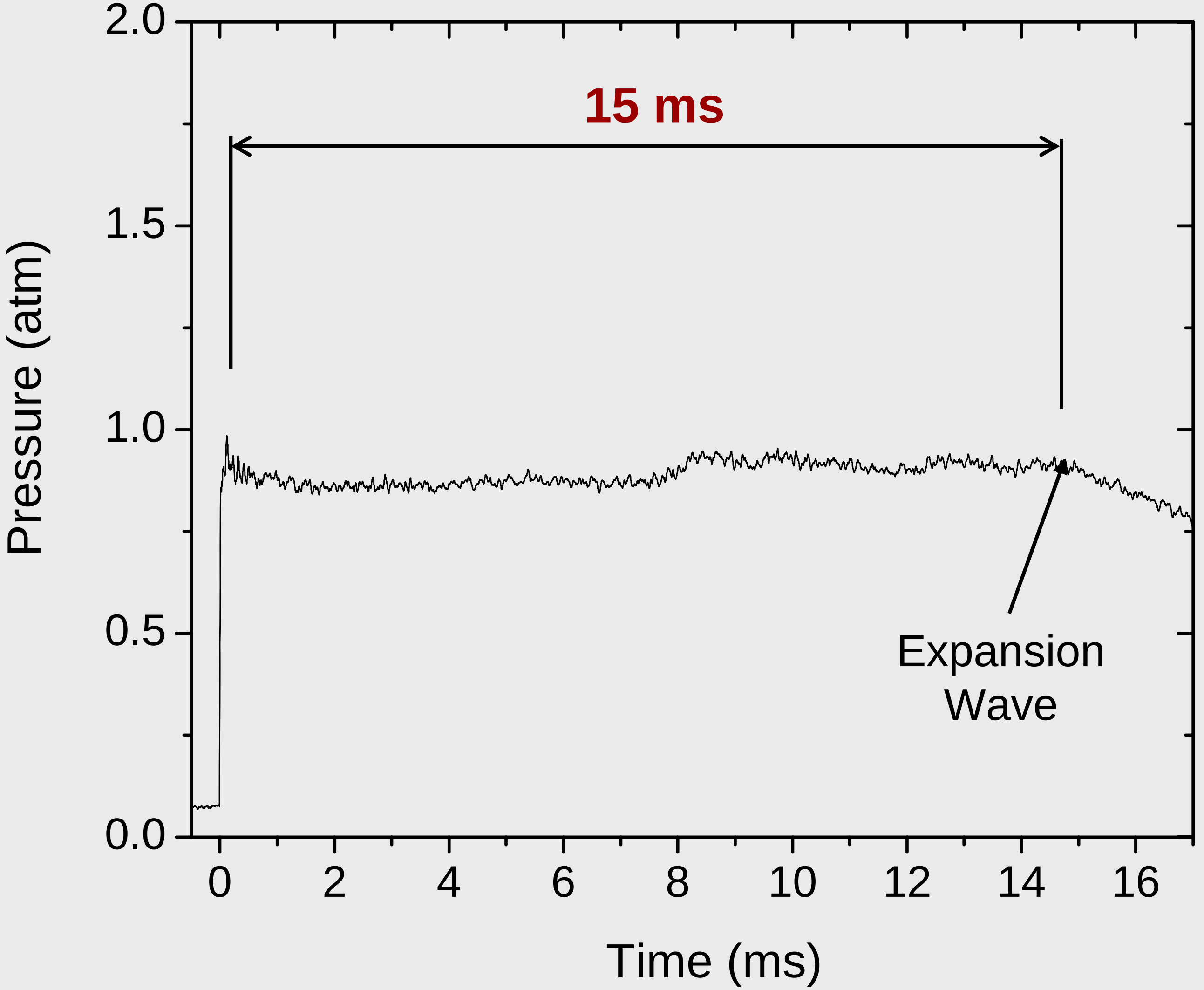
Gas Dynamics Laboratory
University of Central Florida

Task 2 – Autoignition

Experiments with ***Extended Test Time Demonstrated***

T_5 = 891 K
P_5 = 0.87 atm

Driver: 45% C_3H_8
+ 55% He
Driven: Ar



Task 1 – Matrix Development

Experiment Parameter Space Constrained by GT Application

Fuel Blends:

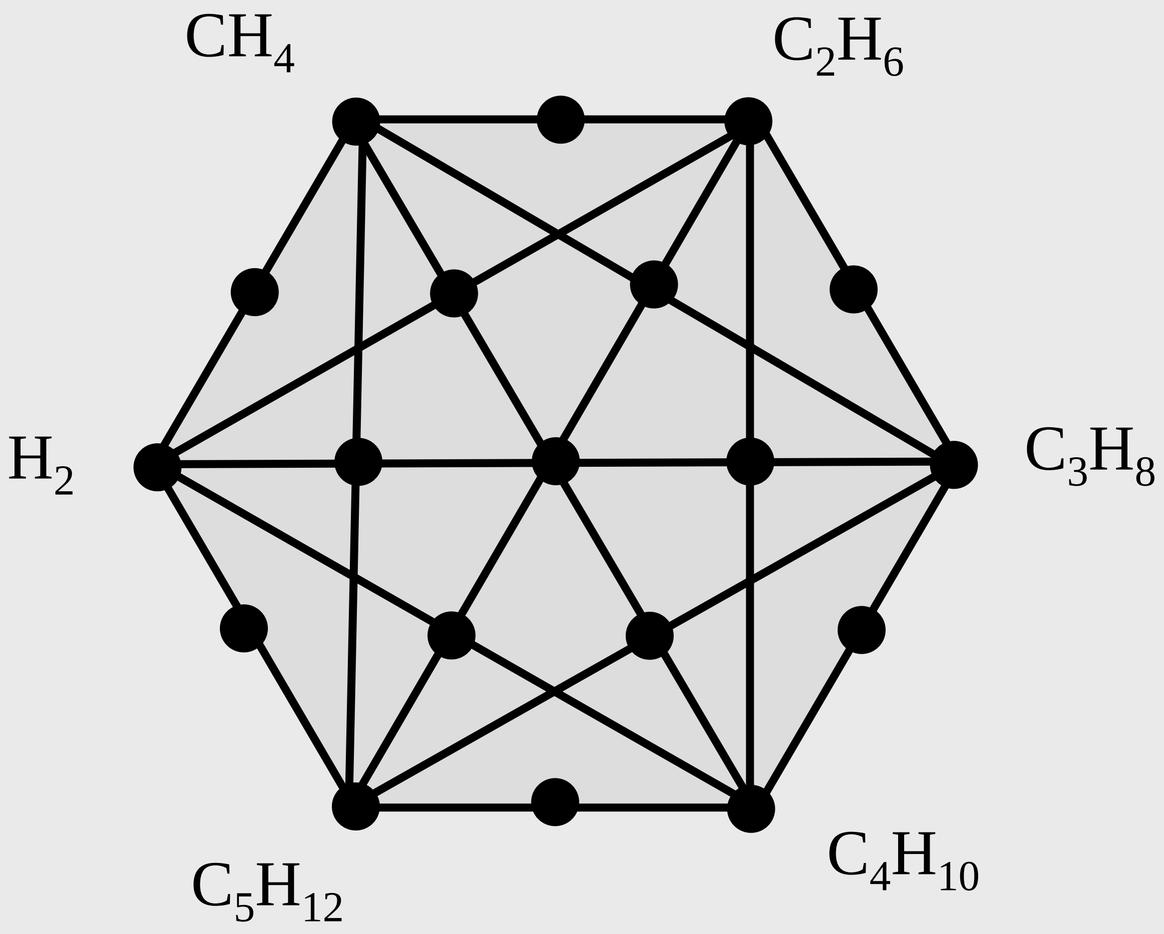
- C_2H_6 0, 20, 40 %
- C_3H_8 0, 15, 30 %
- C_4H_x 0, 10, 20 %
- C_5H_x 0, 5, 10 %
- H_2 0, 10, 20 %
- Balance CH_4

5 factors, 3 levels
⇒ **243 blends!**

Gas Dynamics Laboratory
University of Central Florida

Task 1 – Matrix Development

Statistical Mixture Theory Used To Develop ***DOE Matrix***



Gas Dynamics Laboratory
University of Central Florida

Task 1 – Matrix Development

21-Test Matrix of Fuel Blends Designed for Autoignition Tests

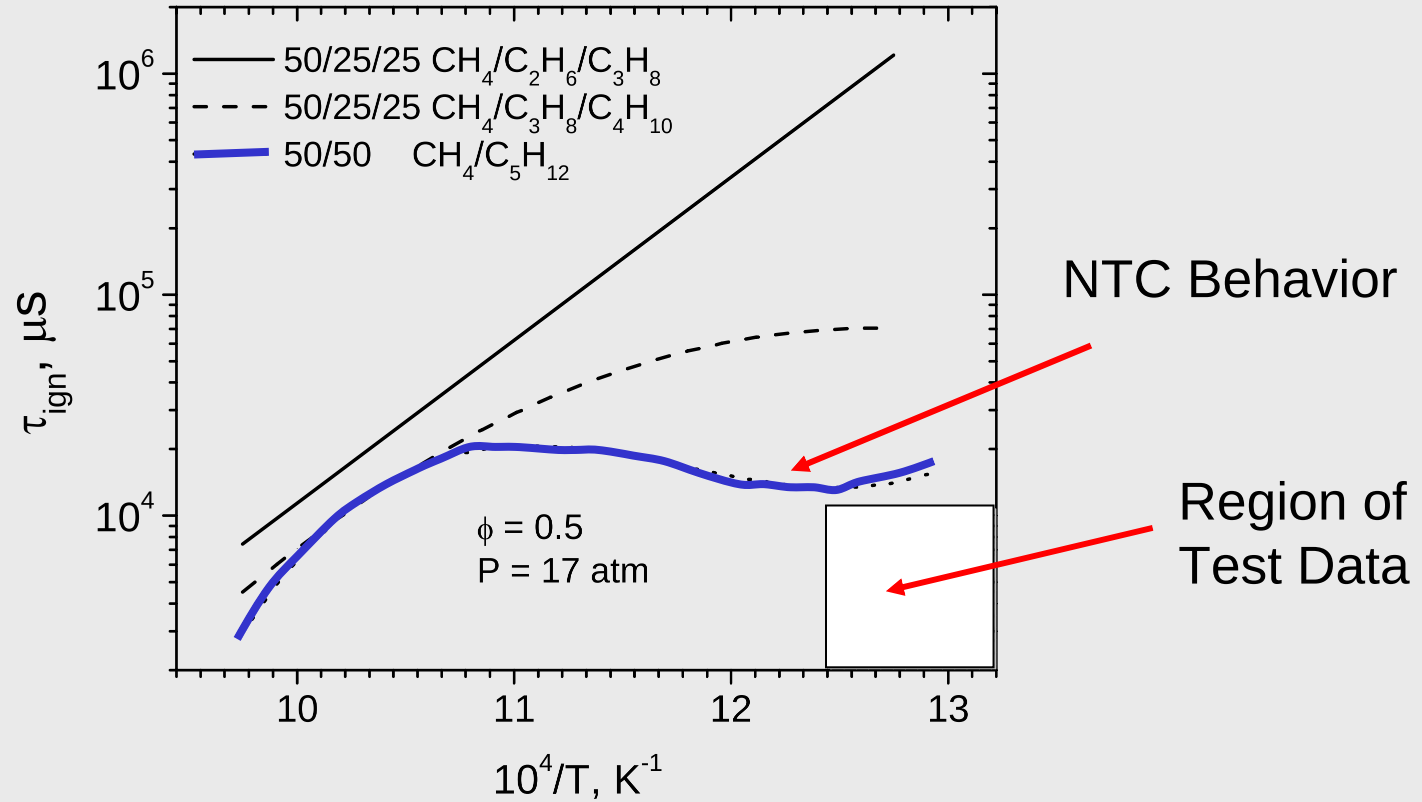
mix #	x_{CH4}	x_{C2H6}	x_{C3H8}	x_{C4H10}	x_{C5H12}	x_{H2}
1	100	0	0	0	0	0
2	75	25	0	0	0	0
3	75	0	25	0	0	0
4	75	0	0	25	0	0
5	75	0	0	0	25	0
6	75	0	0	0	0	25
7	50	50	0	0	0	0
8	50	25	25	0	0	0
9	50	25	0	25	0	0
10	50	25	0	0	25	0
11	50	25	0	0	0	25
12	50	0	50	0	0	0
13	50	0	25	25	0	0
14	50	0	25	0	25	0
15	50	0	25	0	0	25
16	50	0	0	50	0	0
17	50	0	0	25	25	0
18	50	0	0	25	0	25
19	50	0	0	0	50	0
20	50	0	0	0	25	25
21	50	0	0	0	0	50

Gas Dynamics Laboratory
University of Central Florida

Task 2 – Autoignition

*Data Seem to Exhibit **NTC Behavior** Seen in Higher HC*

Calculated Results and Region of Test Results

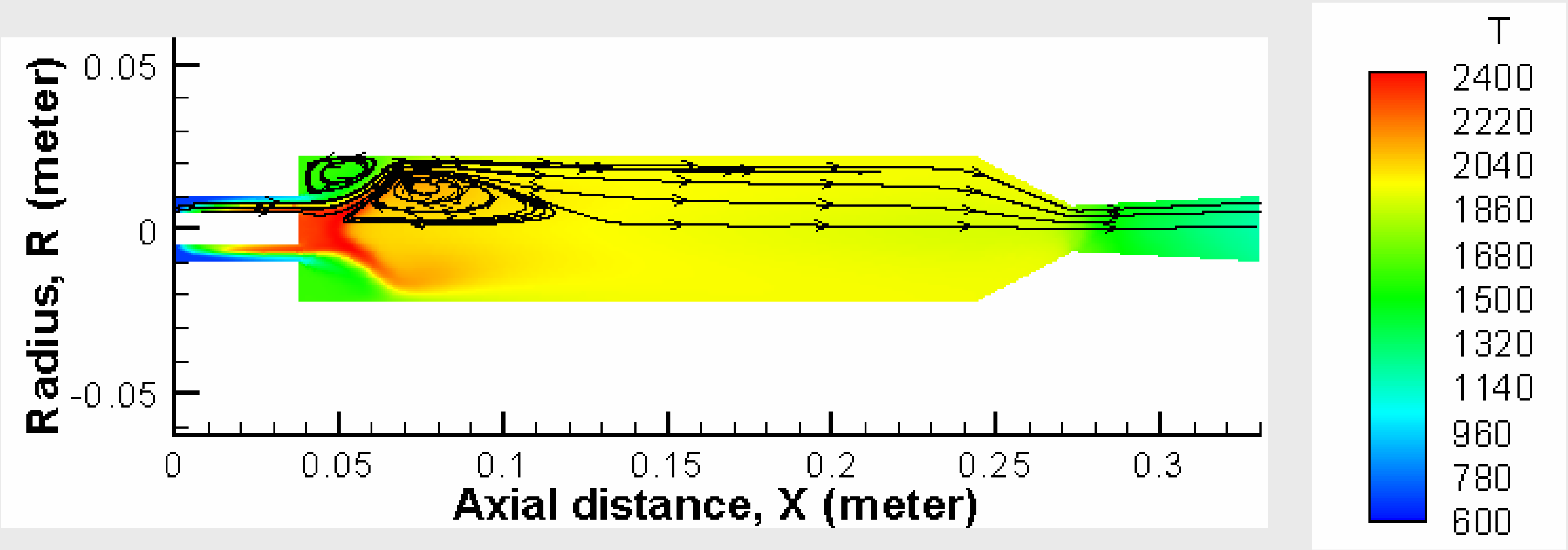


Gas Dynamics Laboratory
University of Central Florida

Task 5 – CFD Model

Flow Parametrics

Penn State Burner Chosen as Model Geometry



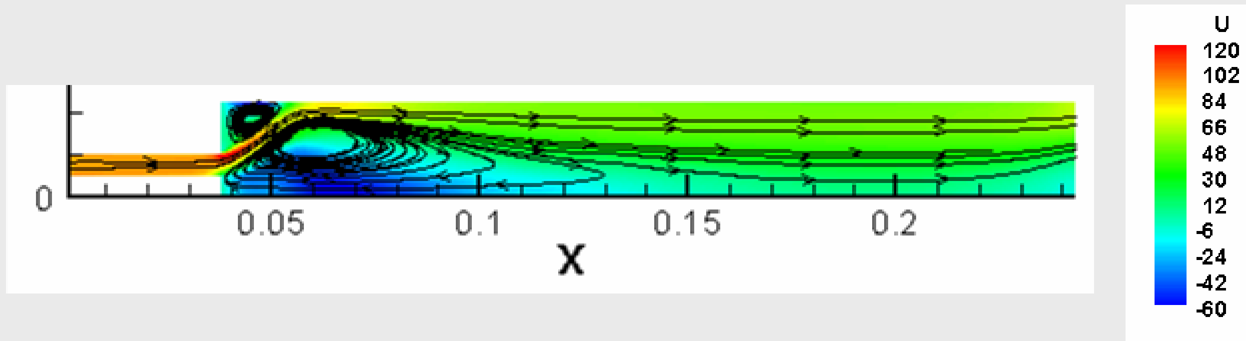
- **Lean Premixed, Swirl Stabilized**
- **Methane, $\phi = 0.6$**
- **Inlet: 0.46 MPa, 660 K**

Gas Dynamics Laboratory
University of Central Florida

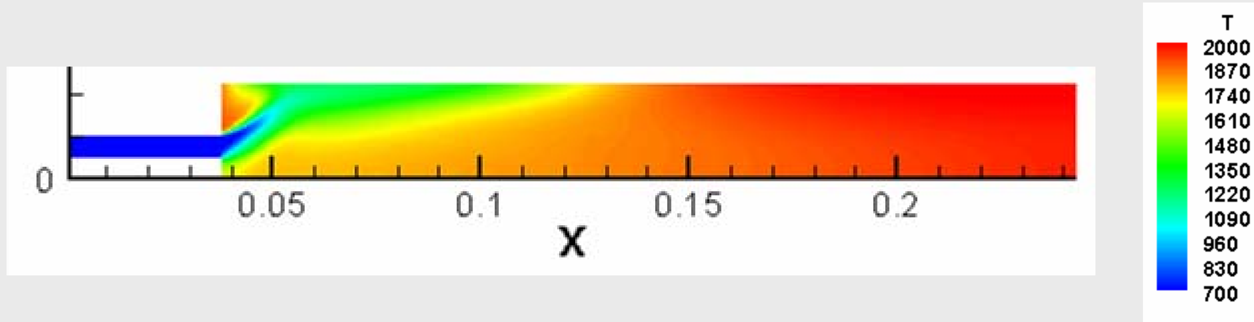
Flow Parametrics

Finite-Rate CH_4 Chemistry, $\phi = 0.6$

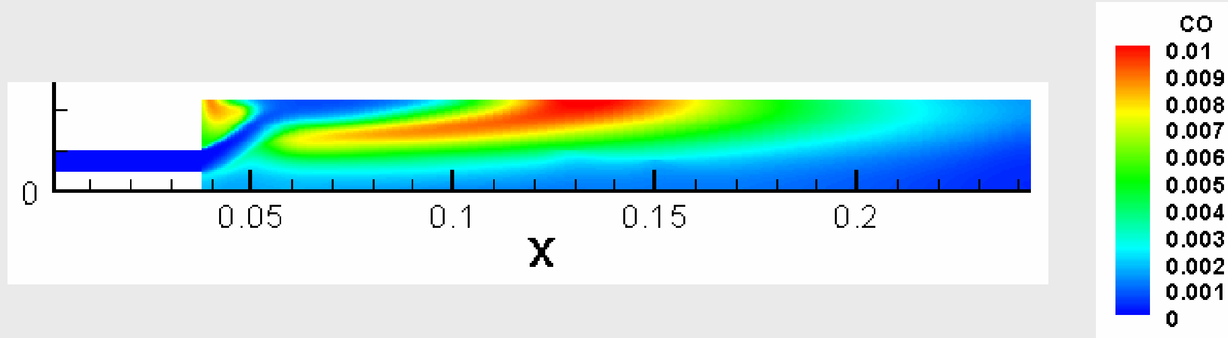
Axial velocity w/ streamlines



Static temperature



CO mass fraction



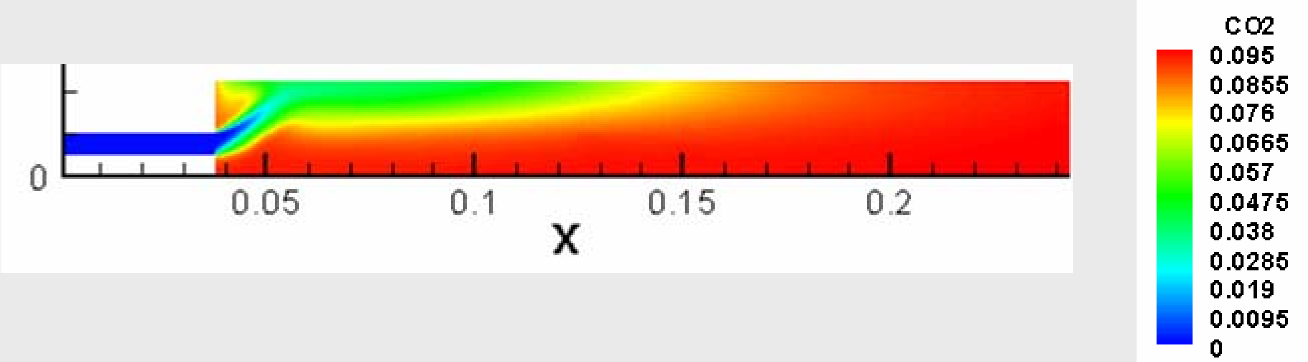
Gas Dynamics Laboratory
University of Central Florida

Task 5 – CFD Model

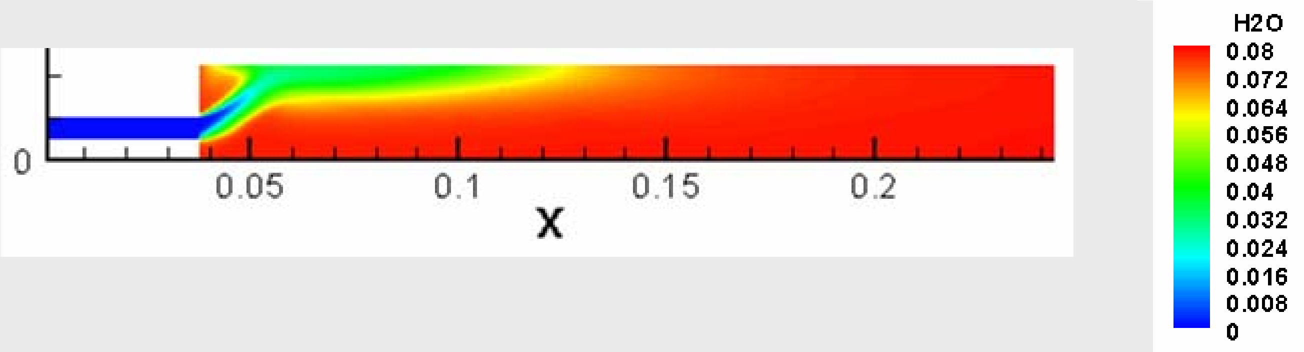
Flow Parametrics

Finite-Rate CH_4 Chemistry, $\phi = 0.6$

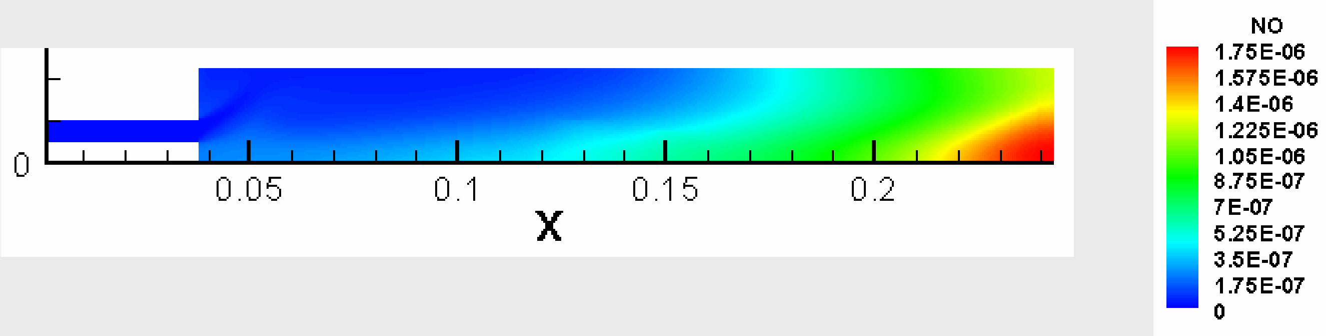
CO2 mass fraction



H2O mass fraction



NO mass fraction



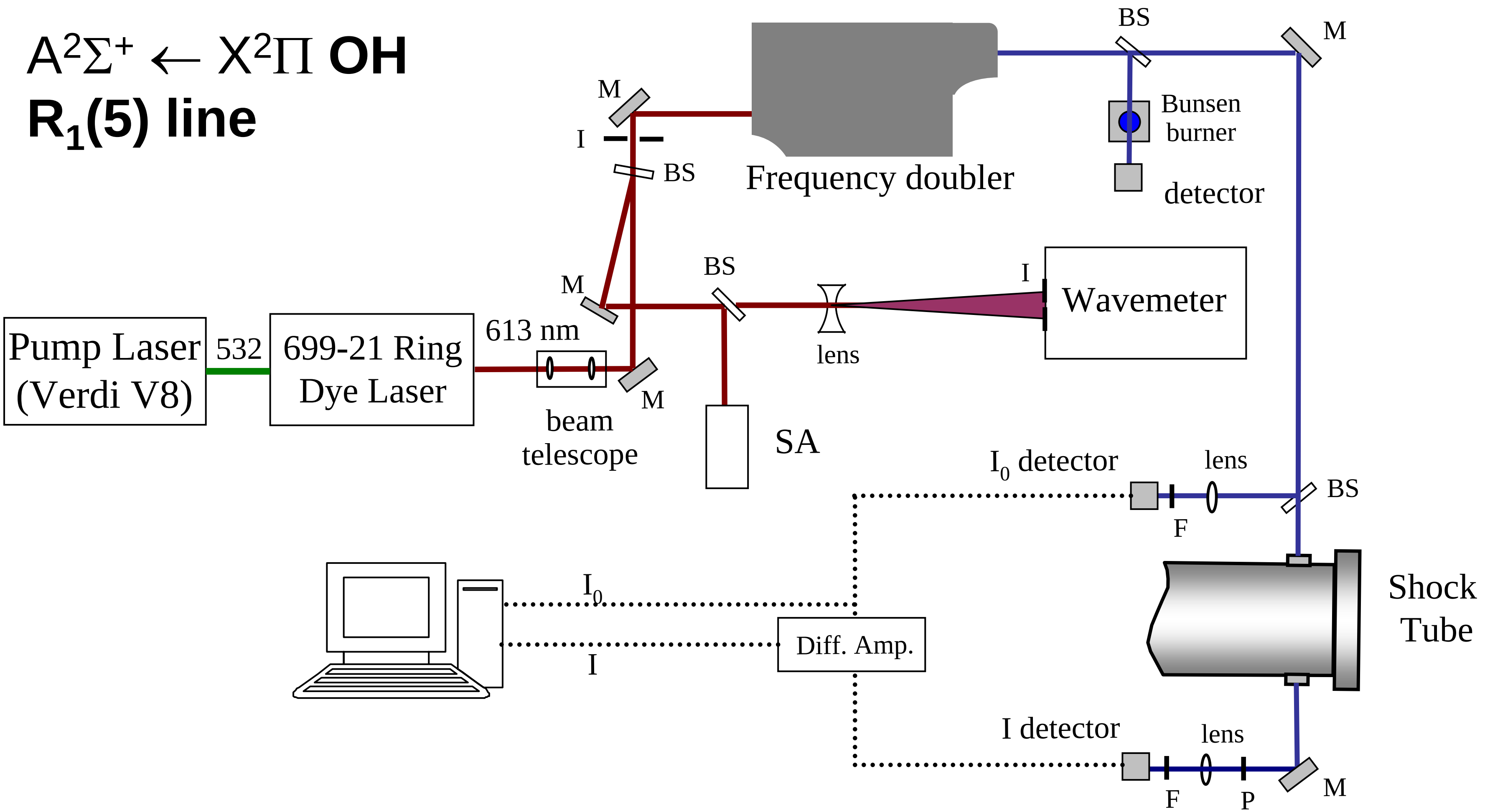
Gas Dynamics Laboratory
University of Central Florida

Task 7 – Mechanism Validation

THE AEROSPACE CORPORATION

OH Conc. Time Histories can be Obtained by Laser Absorption

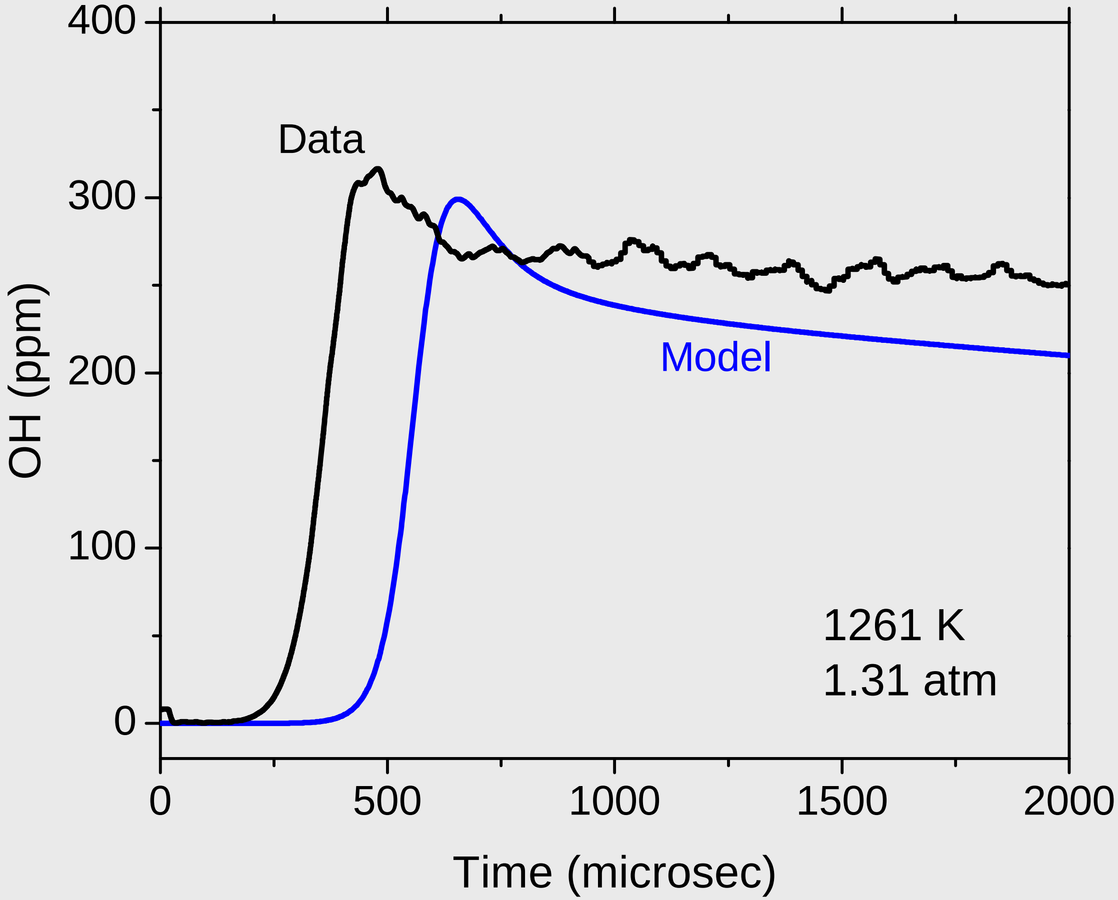
$A^2\Sigma^+ \leftarrow X^2\Pi$ OH
$R_1(5)$ line



Gas Dynamics Laboratory
University of Central Florida

Task 7 – Mechanism Validation

Comparison between Model and OH ppm for Dilute Mixtures



- $0.4\%H_2$ + 0.6%CO + 1% O_2
- 98.0% Ar
- $R_1(5)$ line
- $\nu_c = 32617.46\ cm^{-1}$

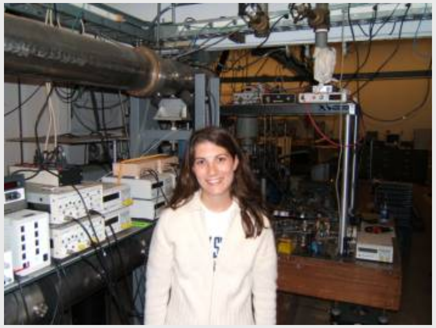
Gas Dynamics Laboratory
University of Central Florida

Summary

1. Lean Syngas Ignition Times Obtained.
2. Lean Methane Fuel Blend Ignition Times Measured.
3. Kinetics Models for Syngas and CH_4 Identified.
4. Autoignition Matrix Completed.
5. CFD Model and Geometry Established.
6. Mechanism Validation Tests Underway.

Gas Dynamics Laboratory
University of Central Florida

Questions?



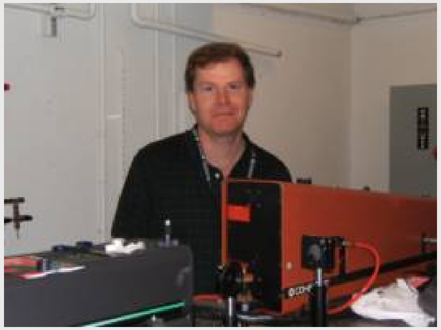
Danielle Kalitan

Joel Hall

Jaap de Vries

Tony Amadio

Stefanie Simmons



Dr. Mark Crofton (Aerospace)

Gas Dynamics Laboratory
University of Central Florida