Development of Criteria for Flameholding Tendencies within Premixer Passages for High Hydrogen Content Fuels

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UTSR Workshop
The Ohio State University

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Contract DE-FE0007045; Joe Stoffa, Contract Monitor

Motivation

Trends in Advanced Lean Burning Gas Turbines*

- Higher Combustor Inlet Temperatures
- Improved Fuel/Air Mixing
- Risk of Auto-Ignition/Flashback
- Role of Fuel Type/Composition

Major Question

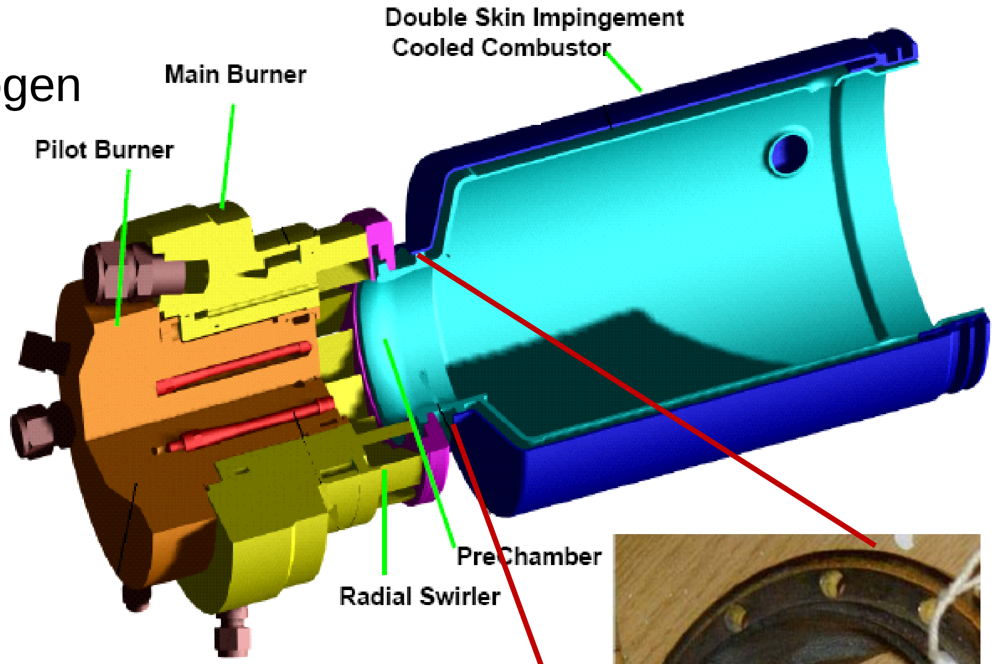
If a Reaction is Initiated in the Premixer,

Will the Reaction be "Held" on a Wall Recess?

* Stationary Gas Turbine Engines

Motivation

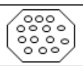
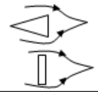
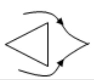
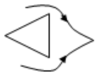
High Hydrogen Content Fuels On N.G. injectors



Desired:
Tools to guide premixer design for robustness relative to flame attachment and disgorgement

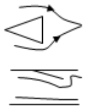
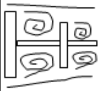
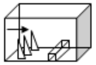
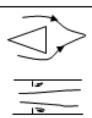
Background

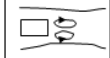
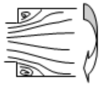
Literature

Reference	Geometry	Fuel	Operating Conditions	Blockage Dimensions	Measurements Made	How	Keywords	Comments
Ale, 1997 (1).		CH4, H2, C3H8	294-623K, 1 atm	N/A	Flammability, Pressure, Excess Oxygen		Flammability Limits	
Balachandar, 1991 (2).		N/A	N/A	b/B = 0.1, 0.13, 0.19, 0.24, 0.325, etc.	Cavitation wrt blockage and Re			Cavitation in Water Tunnels
Baum, 1995 (3).		HC Flames	4-8 m/s	N/A			Numerical Analysis	
Beer, 1972 (4).				(d/D) = 0.54, 0.25, 0.11	Width of recirculation eddy and mass flow rates wrt blockage ratio		Flameholding, Flame stabilization, blockage ratio, ignition time	
Beer, 1965 (5).		Coal		N/A			Residence time	
Bosque, 1983 (6).		Propane	4-9 m/s, Ambient Temp. and Press., Re = 10000-20000	9 FH's w/ 63, 73, & 85% blockage and 2 counterbore sizes	Blowout flammability limits wrt ref velocity and Re			
Choudhury, 1962 (7).		Propane	100-250 ft/s, 1300-1500K, ϕ = 0.7-0.9	Thickness of luminous zone from 0.07-0.12 in.	Blowoff velocity, flame front angle, turbulence,		Wall Recess, flame stabilization	
Copper, 1980 (8).		Jet A Fuel	35 m/s, 0.3MPa, 600-1000K, ϕ = 0.6-0.72	75% flameholder blockage (water cooled)	NOx emission index, CO emission index		Flameholding	
Egolfopoulos, 1997 (9).		Methane	35 m/s, 0.3MPa, 200-1700K, ϕ = 0.70		Extinction Strain Rates		Extinction of premixed flames	
Gat, 1980 (10).		Methane	Turbulence intensity = 0 - 45 cm/sec, Re = 0-150, EGR from 0 to 30%, T=340K, P=1atm		Effect of Exhaust gas recirculation due to increase in single wall quenching distance.		Quenching distance, Turbulence intensity	
Jones, 1978 (11).		aircraft fuels (petroleum, JP-4, ASTM Jet-A, Diesel No. 2, oil shale, coal) and propane	P = 3-30 atm, T = 475-800 K, f/a = 0.12 to 1.51		Emission reductions for different combustors			No results, just refers to studies to be performed
Ju, 1997 (12).		Methane	Volumetric percentages of methane in air = 4.0-6.53, flame velocity = 20 cm/s, T = 1200K - 1800		Extinction Strain and Stretch Rates, Fraction of heat loss		Flammability Limits, extinction limits, premixed flames	
Kanury, 1975 (13).		Gaseous, liquid and solid fuels						Introduction to flameholding, bluffbody flame stabilization, flammability limits, etc.
Katta, 1998 (14).		Propane	Numerical analysis of 30 - 42 m/s, 1750 K max, C_D = 0.125-0.151		ΔC_D from addition of disk to forebody geometry, Rate of mass remaining in		Numerical Analysis, Trapped Vortex	
Kojima, 1993 (15).		n-Butane	20-120 NLM, 99.5% butane mixture with air, T_i = 340K, P_i = 0.10 Mpa	Swirl Chamber	autoigniton delay times			
Lee, 1994 (16).		Methane	Mole fractions of 4 to 6%, T = 0-1700K, Axial velocity = -100 to 50 cm/s		Weak and strong interactions of flames for certain temperatures and flame position.		Extinction of interacting flames	
Lefebvre, 1976 (17).		Methane, Propane	0-30 m/s, 0.08-0.5 atm, Turb int. 2.5-15%		Quenching distance for different pressures, equivalence ratios		Quenching distance	distance increases with increase in Turb int., Thermal diffusion is important.
Lefebvre, 1979 (18).		Propane (gaseous)	10-100 m/s, 0.2-0.9 x 105 N/m2, T = 300, 370, 430, 500, 575K, Turb. Int. = up to 15%	Flameholder diameter = 2-12 cm, 4-34%	Temp, Press, Velocity, Fuel Flow until extinction		Weak Extinction Limits, Blockage, Flame holding	
Lefebvre, 1980 (19).		Iso-Octane, Oils	F/A (by Wt) 0.066-0.073, 15-75 m/s, 0.2-1.0 x10^5 N/m^2, $T_{(air)}$ = 290K, Turb Int. = 2-	Bg = (cone dia/pipe dia)2 = 0.04-0.34	Temp, Press, Velocity, Fuel Flow until extinction		Weak Extinction Limits, Blockage, Flame holding	
Lefebvre, 1992 (20).		JP5 (liquid kerosene)	Mach # = 0.18-0.26, Ti = 650-850K, ϕ = 0.15-0.6	FH Width = 25.4-65.1 mm, FH angle = 45, 60, 90°, FH Blockage = 0.125-0.32	Temp, Press, Velocity, Fuel Flow until extinction		Weak Extinction Limits, Blockage, Flame holding	
Lefebvre, 1983 (21).		N/A	N/A				Weak Extinction Limits, Blockage, Flame holding	Chapter has many figures, equations, and subject matter pertinent to project.

Background

Literature

Lefebvre, 1986 (22).		Jet A Fuel	47-78 m/s, T = 773, ϕ = 0.6-1.2	Single-Sided FH 15-90o, and 60o V-Gutter	Pressure, Temperature, Velocity		Flameholding, Blockage effects	Prediction of drag coefficient for certain blockage
Lefebvre, 1975 (23).		Propane	up to 50 m/s, ϕ = 0.5-2.0, 0.17 atm, Turb. Int. = 1-22%		Pressure, Temperature, Velocity, quenching distance, minimum ignition energy		Quenching distance, Minimum ignition energy	
Turns, 1996 (24).								Introduction to Combustion subjects such as flameholding, bluffbody flame stabilization, flammability limits, quenching, etc.
Little, 1979 (25).		N/A	100 ft/s, Re = 0.64 x 10^6	Spindal dia = 3/8 in to 11/8 in	Afterbody Drag, Velocity, shear stress, flow visualization		Trapped vortex	
Maekewa, 1975 (26).	N/A	Methane	P = 0 - 0.4 kg/cm^2,	N/A	Pressure, Temperature, Velocity, quenching distance		Flame Quenching	
Mastorakos, 1997 (27).	N/A	Non-Premixed	N/A	N/A	N/A		Autoignition, Direct numerical simulation, conditional moments, modeling	
Nair, 1973 (28).		Butane	Up to 2 atm, ϕ = 0.85-1.1, 300K		Pressure, quenching distance		Flame Quenching	
Noda, 1995 (29).		N/A	Turbulence intensity = 0-30%	Blockage Ratio = 0.02-0.16	Drag Coefficient, Blockage factor, downstream surface drag		Blockage effects	
Oancea, 1997 (30).		Methane, Propane	ϕ = 0.73-1.44, P = 40-104 kPa, T = 298-		Pressure, quenching distance		Flame Quenching	
Plee, 1978 (31).		Propane (gas and liquid), Jet A, JP 4, DF 2	10-100 m/s, 0.2-8 atm, T = 300-800K	45° conical baffle, tube-and disc, disc-in-duct	Pressure, Temperature, Velocity, Lean blowoff limit			

Roberds, 1989 (32).		N/A	144-319 ft/s, 13.5-14 psi		Pressure, Temperature, Velocity, Residence time			
Roffe, 1978 (33).		Propane	Pi = 10 atm, ϕ = 0.3-0.7, Ti = 800K, 20-35 m/s	Wire Grid (60, 73%), Perforated plate (70-80%), multiple cone (70-80%), Vee Gutter (70-80%), Single Cone (70-80%),	Pressure, Temperature, Velocity, NOx, CO, HC emissions			
Shih, 1996 (34).		Methane	680 K, 8.9 m/s (Re # = 660), Airflow rate = 1.2 SCFM, ϕ = 0.4-1.1		Pressure, Temperature, Velocity, NOx emissions			
So, 1988 (35).		N/A	10-15.6 m/s, Rotational speed = 0-840 rpm, Inlet centerline Turb = 4.6-17.6 x 10^2, Re = 3.1-4.5 x10^{-4}	Diameter of combustor 38.1-43.2 mm, Step height = 10.15-12.7 mm			Dump Combustor flows, reattachment length, rotation effects	
Van der Lans, 1997 (36).		N/A		40 mm for inner portion, 80 for outer, 155 for largest, 25o inclines			Mixing, residence time distributions, swirl flow, modeling, burner	Cold, confined swirl
Zabetakis, 1965 (37).		200 Combustible gases					Flammability Characteristics, autoignition, and burning rate of 200 combustible gases	
Zhou, 1994 (38).		Methane	Up to 50 atm, ϕ = 0.2-2.0, 650-2400K		Pressure, Temperature, Velocity, Ignition Delay times,		Autoignition	

Background

Large Body of ... olding

Findings

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Studies of

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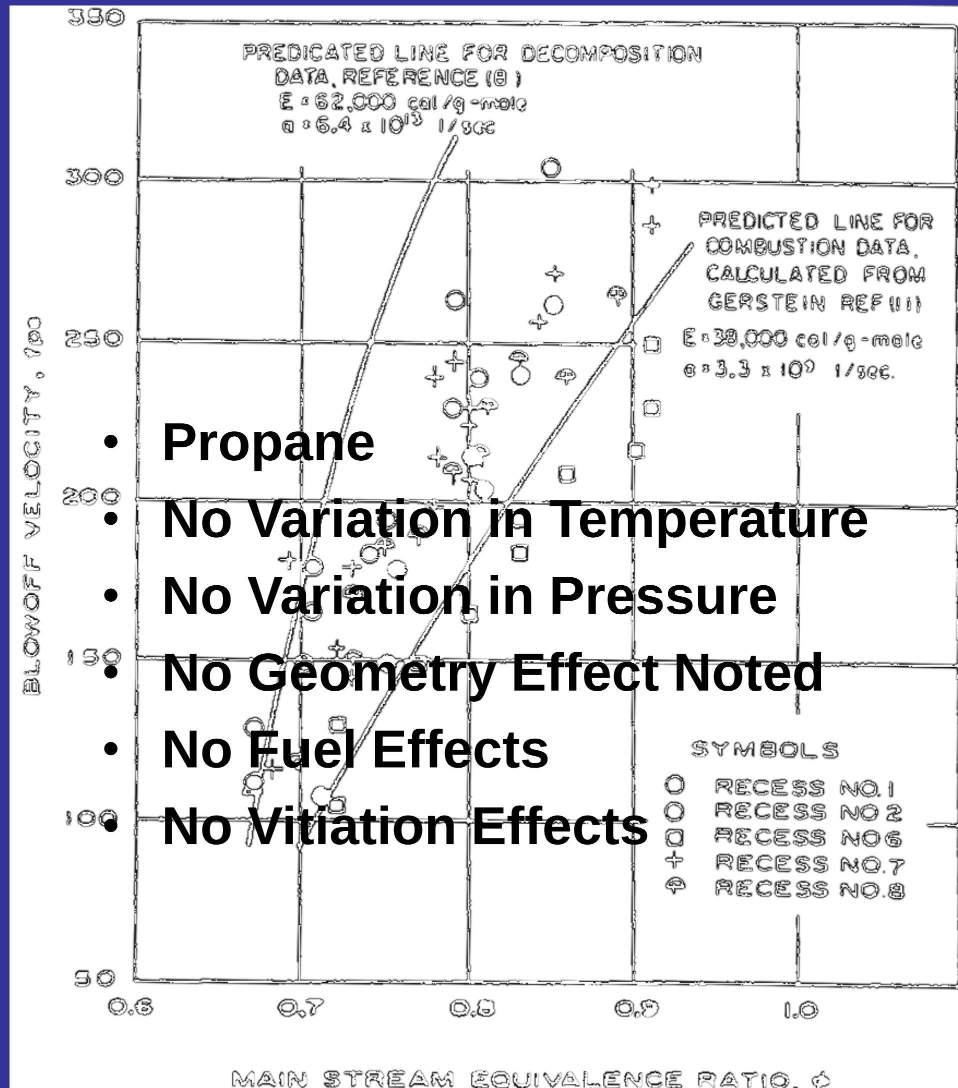


- Propane
- No Variation in Temperature
- No Variation in Pressure
- No Geometry Effect Noted
- No Fuel Effects
- No Vitiation Effects

Background

Large Body of Literature on Blowoff/Flameholding

Findings

- Only ~25% Focus on Natural Gas, <10% Hydrogen
- Most Focus on Centerbody Stabilization vs. Wall Effects
- Most Seek How to Stabilize, Not How to Avoid

Studies of Particular Relevance

- Cambel, et al. (1957, 1962)
  - Wall Perturbations
  - Limited Conditions
  - Suggested Mechanism “Similar to Centerbody Stabilized”
- Correlation work for CB Stabilized
  - Damköhler scaling seems to capture behavior
  - e.g., work of Lefebvre, others
  - e.g., Shanbhogue, Husain, and Lieuwen

Research Questions

Major Question

If a Reaction is Initiated in the Premixer,

Will the Reaction be "Held" on a Wall Recess?

Related Question #1

To What Extent do "Damköhler Type" expressions (based mainly on bluff body stabilized flames) apply to "small" wall recesses and/or perturbations?

Research Questions

Major Question

If a Reaction is Initiated in the Premixer,

Will the Reaction be "Held" on a Wall Recess?

Related Question #2

If the reaction holds on a wall feature, what is required to dislodge it (experience suggests strong hysteresis)

Research Questions

Major Question

If a Reaction is Initiated in the Premixer,

Will the Reaction be "Held" on a Wall Recess?

Related Question #3

What is role of T, P, fuel composition, and level of vitiation?

Research Questions

Major Question

If a Reaction is Initiated in the Premixer,

Will the Reaction be "Held" on a Wall Recess?

Related Question #4

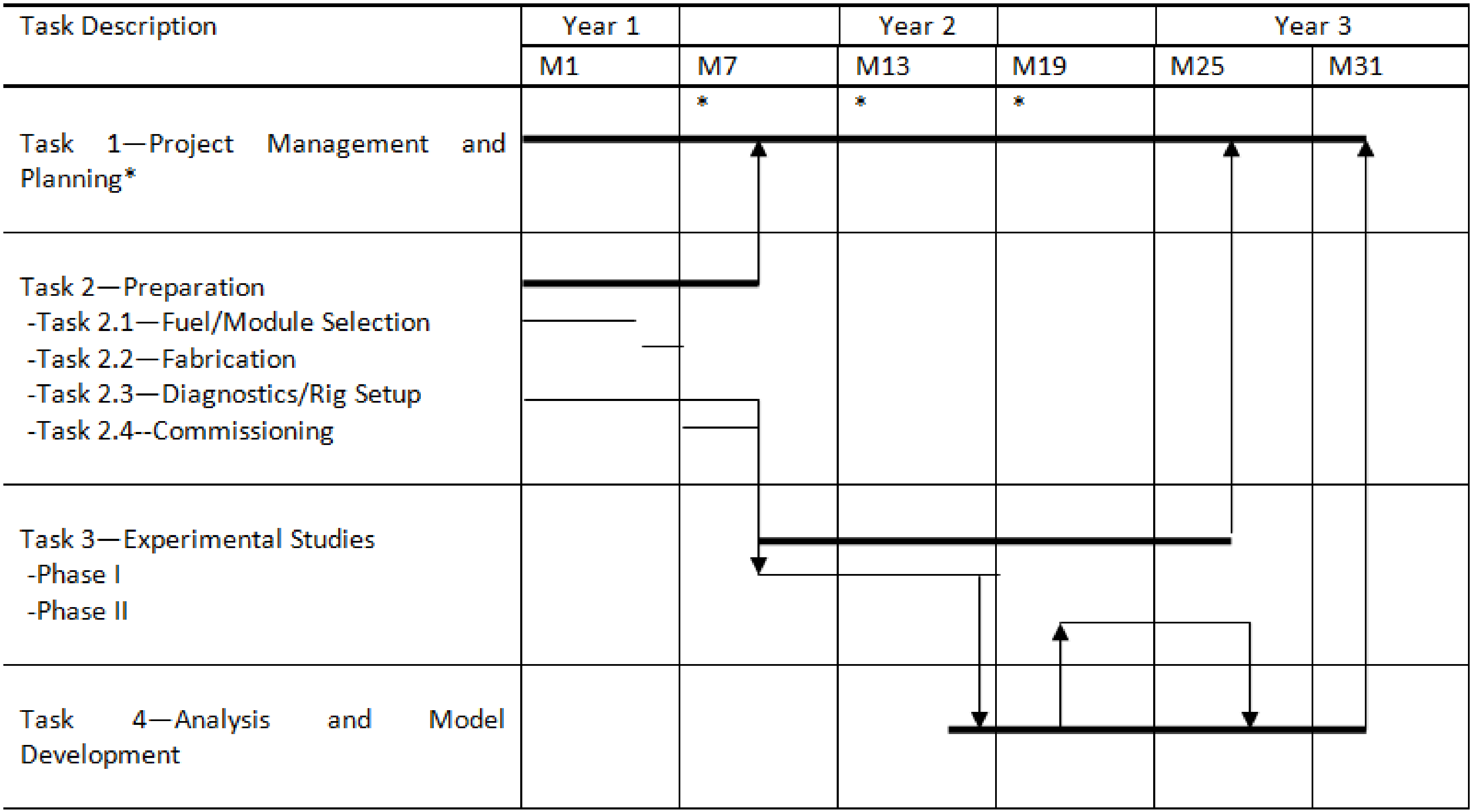
How does the geometry of the wall feature affect the flameholding tendency?

Project Goal

Develop design guides to predict flameholding tendencies within premixer passages as a function of:

- **Pressure**
- **Temperature**
- **Fuel Type/Composition**
- **%O2 in the air (vitiation levels)**
- **Geometry Features**

Approach and Schedule



Approach

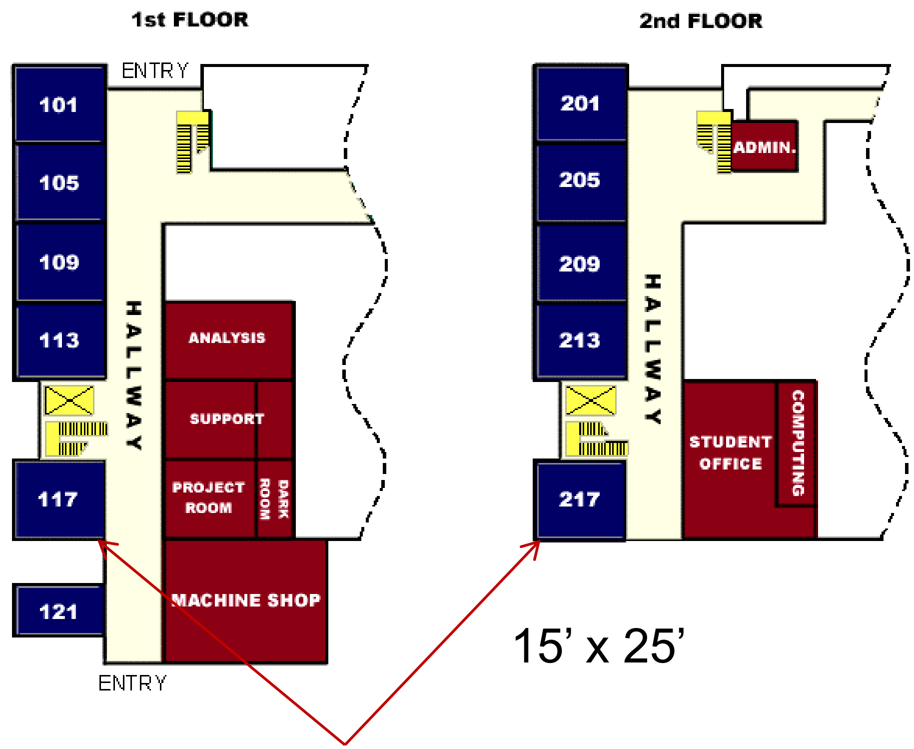
- Preparation
  - Fuel/Module Selection
  - Fabrication
  - Diagnostics / Rig Setup
  - Commissioning

- Experimental Studies

- Analyze and Correlate Results

Preparation

The test rig will leverage existing high pressure testing capability developed through support of NASA, DOE, and industry

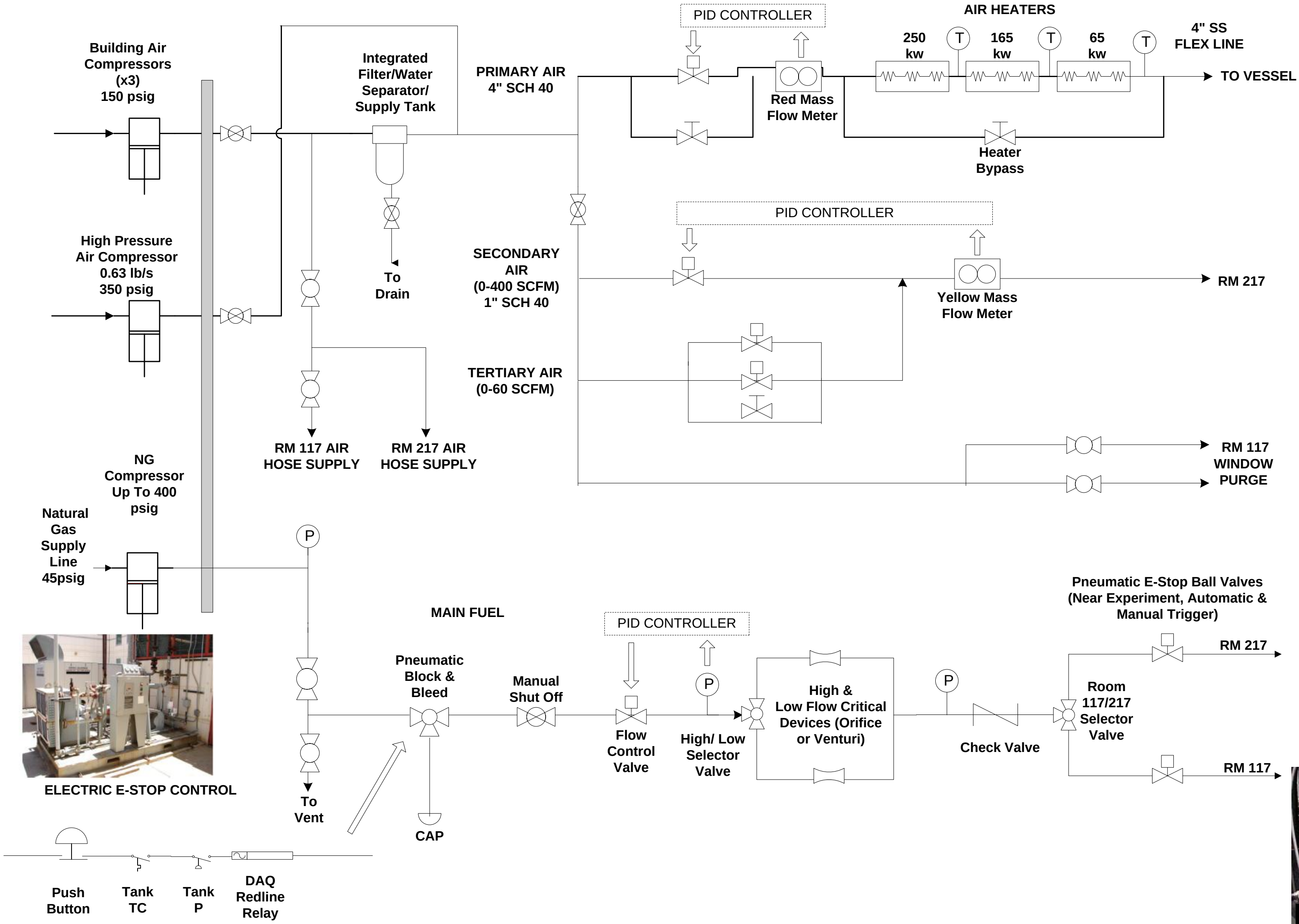


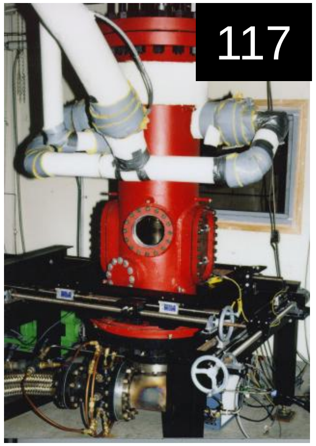
15’ x 25’

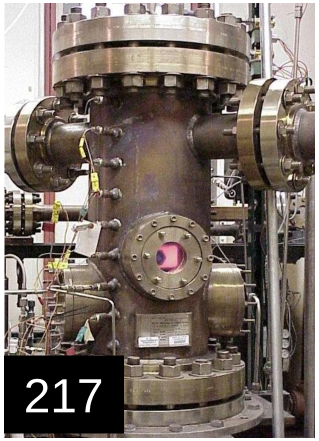
High Pressure Test Cells

4 lb/s air; 1000 deg F preheat; diluents (stored tanks)
Pressures to 18 atm

UCICL HIGH PRESSURE FACILITY 1/08
AIR & NATURAL GAS SYSTEMS

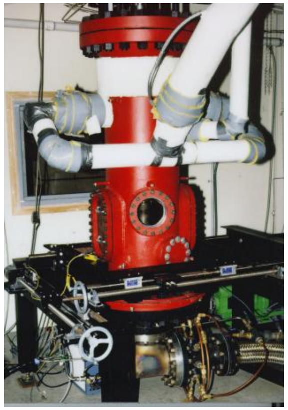


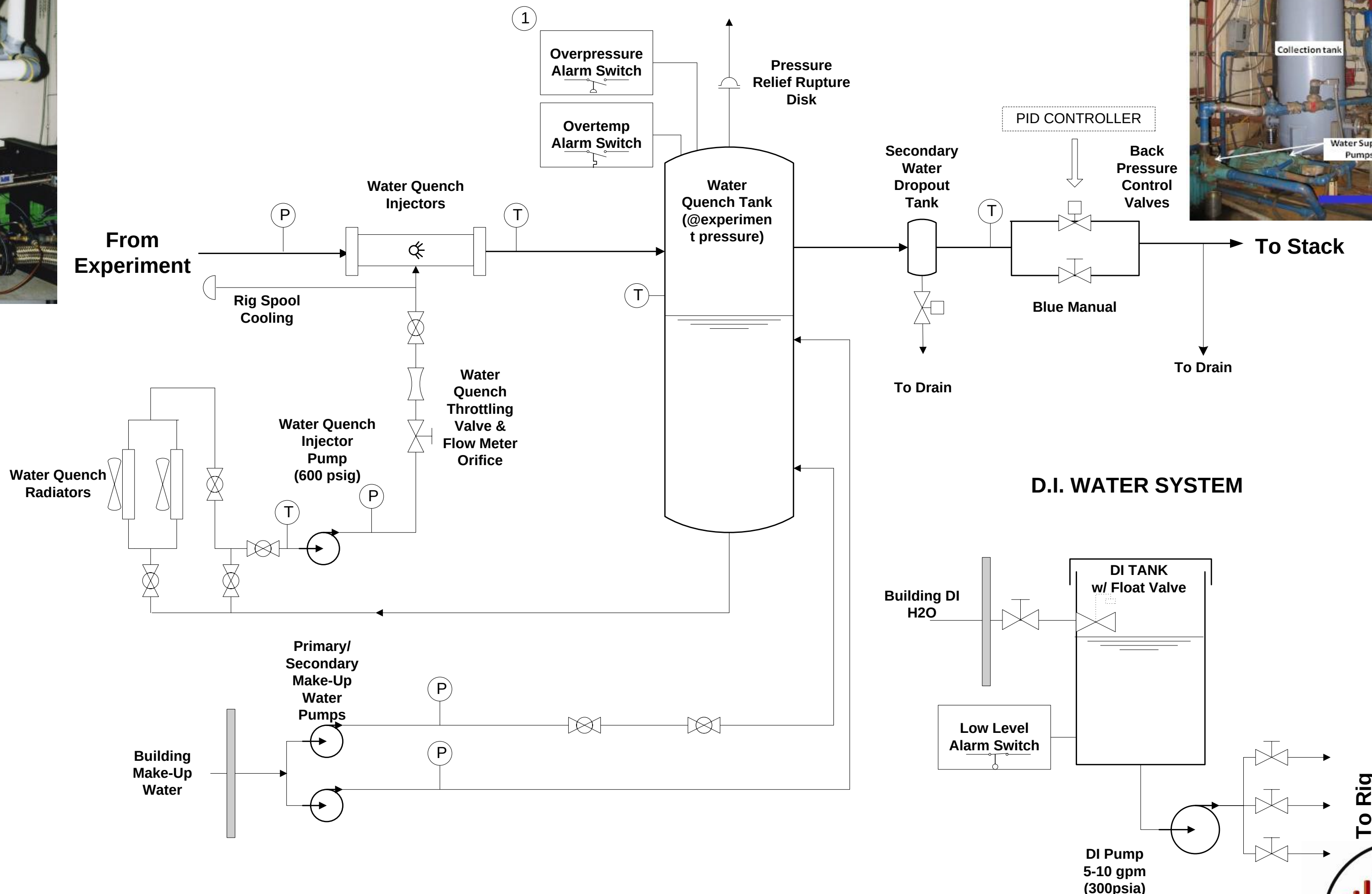


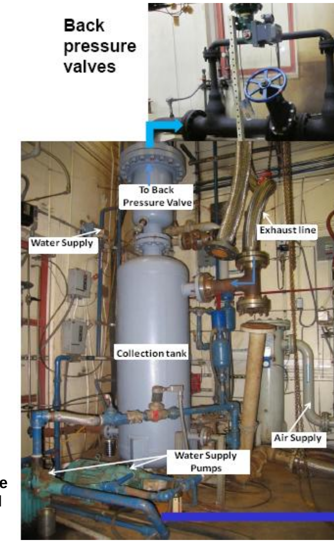


UCICL HIGH PRESSURE FACILITY 1/08

WATER QUENCH & DI WATER SYSTEMS





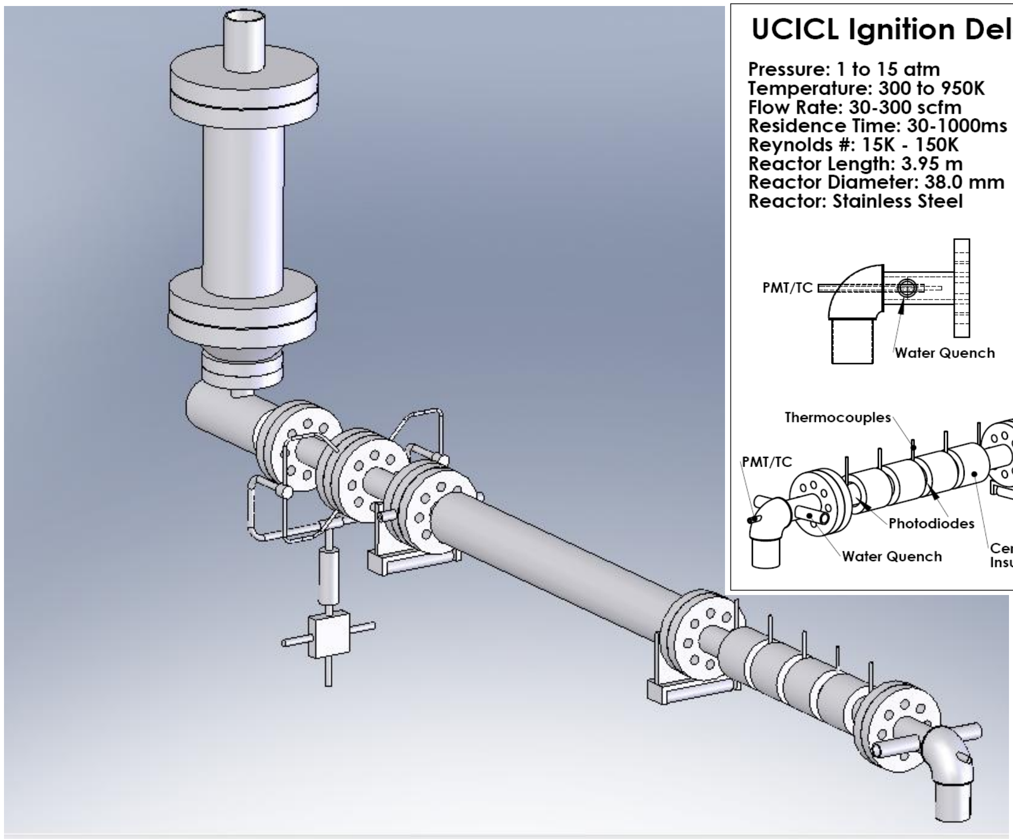


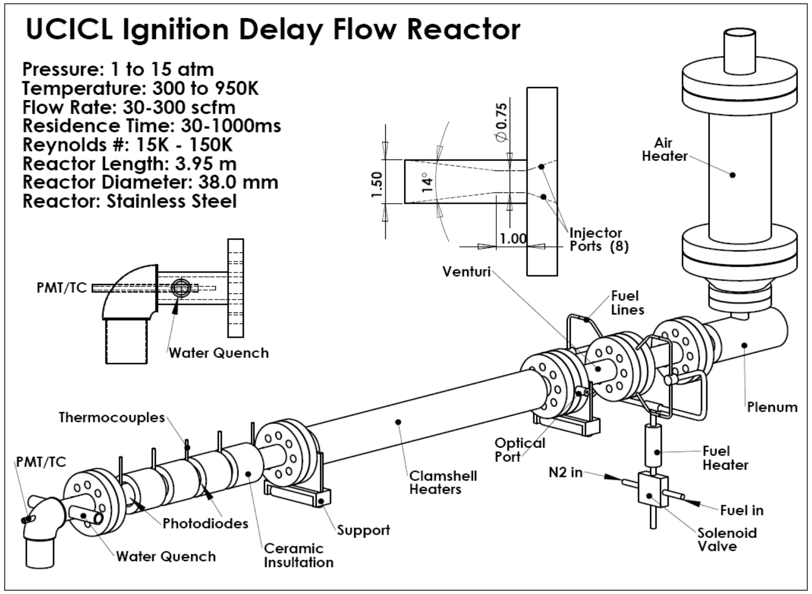
1 Series Contacts with Fuel E-Stop Switches

Preparation

Apparatus

- **Modular, leveraging elements of a flow reactor used for UTSR, CEC, and EPRI supported ignition delay studies**

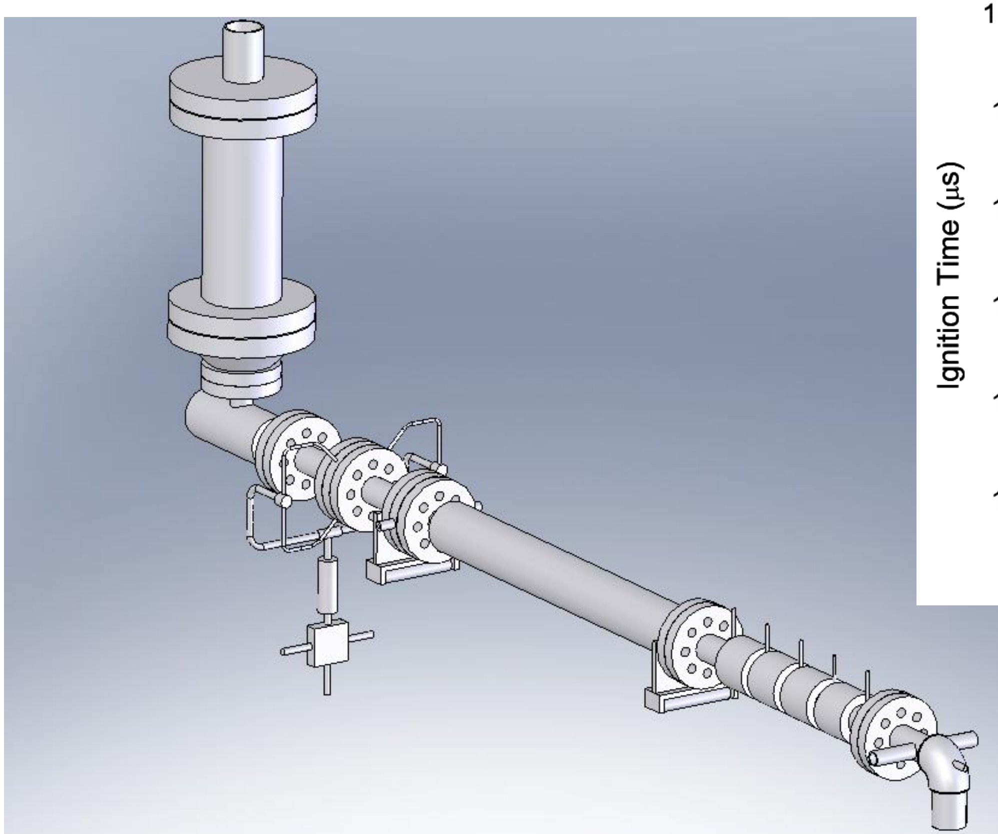


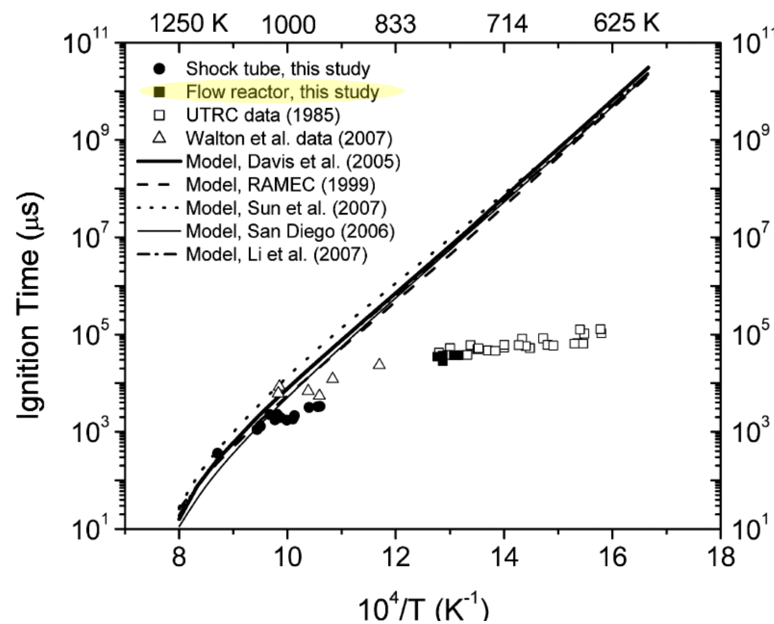


Preparation

Apparatus: Hydrogen/Air ignition

- **Beerer & McDonell (2008): Autoignition of Hydrogen and Air inside a Continous Flow Reactor with Application to Lean Premixed Combustion, J. Engr Gas Turb Power, Vol 130, pg 051507-1**





Available online at www.sciencedirect.com

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Combustion and Flame 149 (2007) 244–247

Combustion and Flame

www.elsevier.com/locate/combustflame

Brief Communication

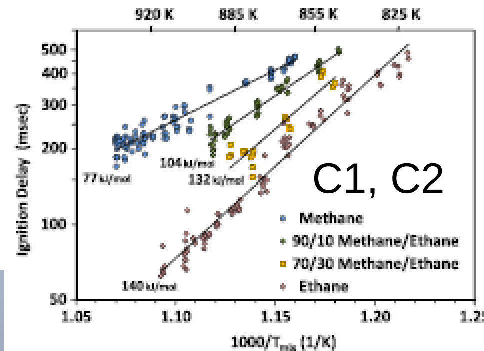
New syngas/air ignition data at lower temperature and elevated pressure and comparison to current kinetics models

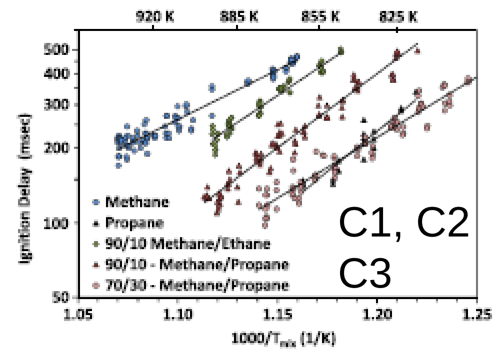
Eric L. Petersen [a,*], Danielle M. Kalitan [a], Alexander B. Barrett [a], Shatra C. Reehal [b], John D. Mertens [c], David J. Beerer [d], Richard L. Hack [d], Vincent G. McDonell [d]

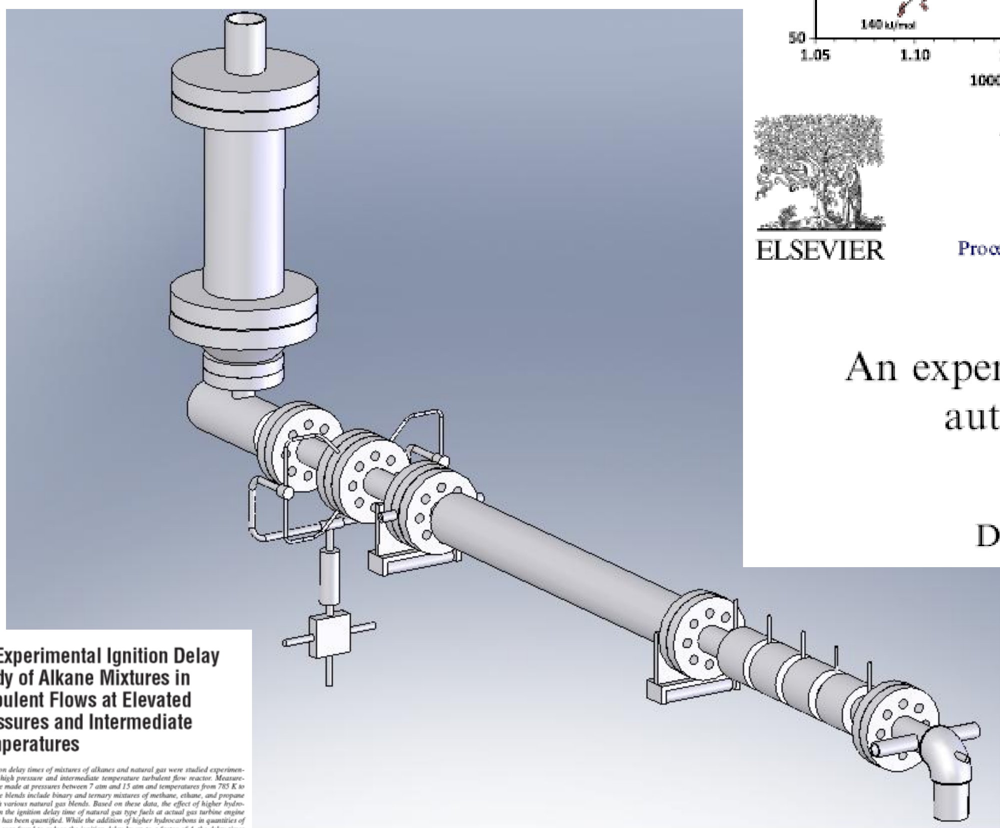
Preparation

Apparatus: Alkanes

- **Beerer and McDonell (2010, 2011)--alkanes**







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ScienceDirect

Proceedings of the Combustion Institute 33 (2011) 301–307

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

An experimental and kinetic study of alkane autoignition at high pressures and intermediate temperatures

David J. Beerer, Vincent G. McDonell *

An Experimental Ignition Delay Study of Alkane Mixtures in Turbulent Flows at Elevated Pressures and Intermediate Temperatures

David Beerer

Vincent McDonell[1]
e-mail: mcdonell@ucicl.uci.edu

Scott Samuelsen

UC Irvine Combustion Laboratory,
Irvine, CA 92697-3550

Leonard Angello
Electric Power Research Institute,
Palo Alto, CA 94304-1395

Autoignition delay times of mixtures of alkanes and natural gas were studied experimentally in a high pressure and intermediate temperature turbulent flow reactor. Measurements were made at pressures between 7 atm and 15 atm and temperatures from 785 K to 935 K. The blends include binary and ternary mixtures of methane, ethane, and propane along with various natural gas blends. Based on these data, the effect of higher hydrocarbons on the ignition delay time of natural gas type fuels at actual gas turbine engine conditions has been quantified. While the addition of higher hydrocarbons in quantities of up to 30% was found to reduce the ignition delay by up to a factor of 4, the delay times were still found to be greater than 60 ms in all cases, which is well above the residence times of most engine premixers. The data were used to develop simple Arrhenius type correlations as a function of temperature, pressure, and fuel composition for design use. [DOI: 10.1115/1.4001981]

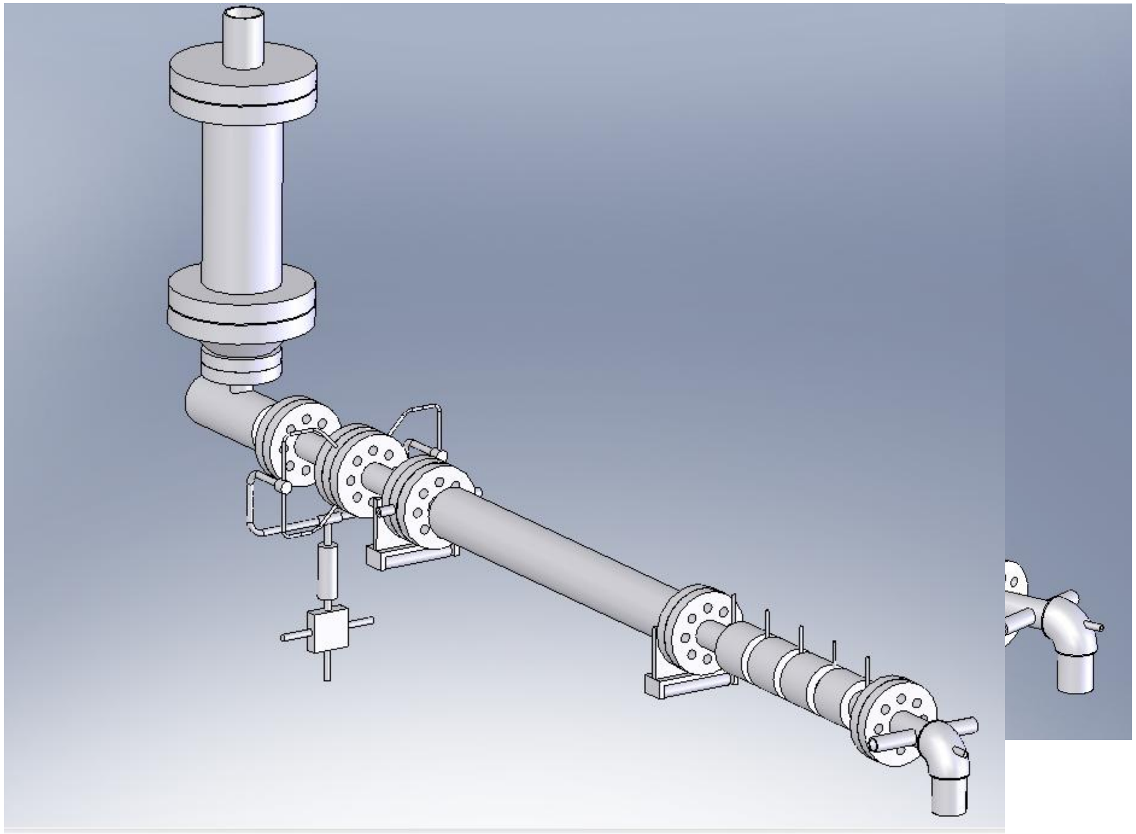
J. Engr Gas Turb Power (2010)

All tabulated data available
In supplemental material
997 ignition measurements

Preparation

Apparatus

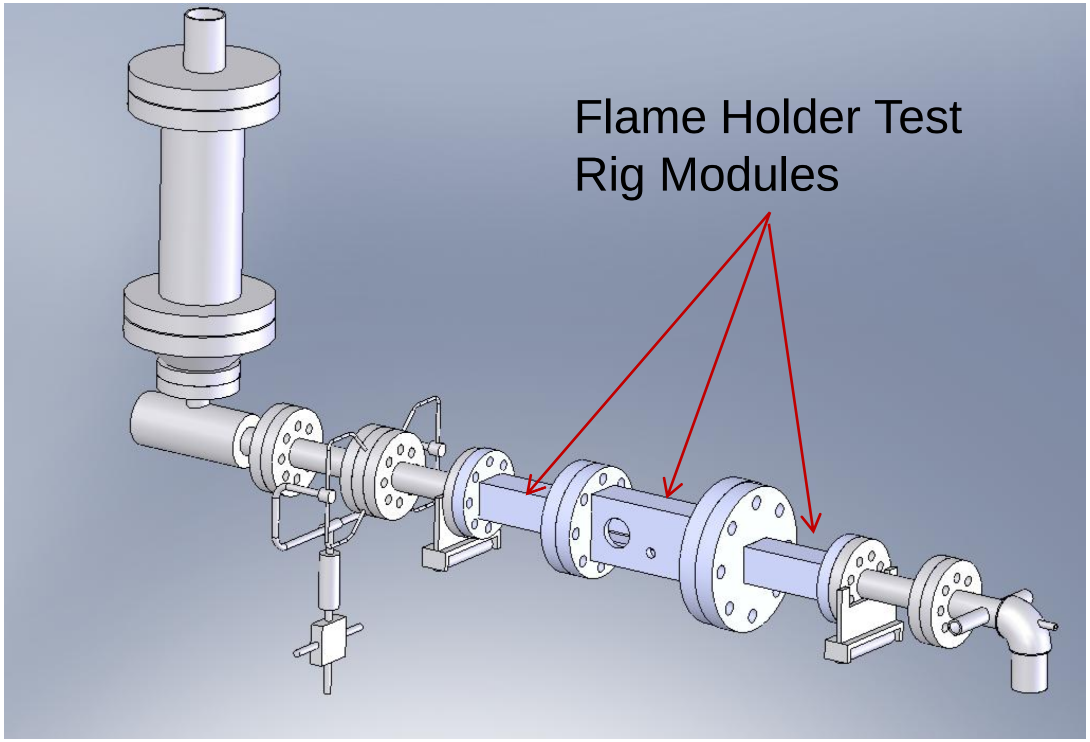
- **Modular, leveraging elements of a flow reactor used for UTSR, CEC, and EPRI supported ignition delay studies**



Preparation

Schematic

- **Modular, leveraging elements of a flow reactor used for UTSR, CEC, and EPRI supported ignition delay studies**

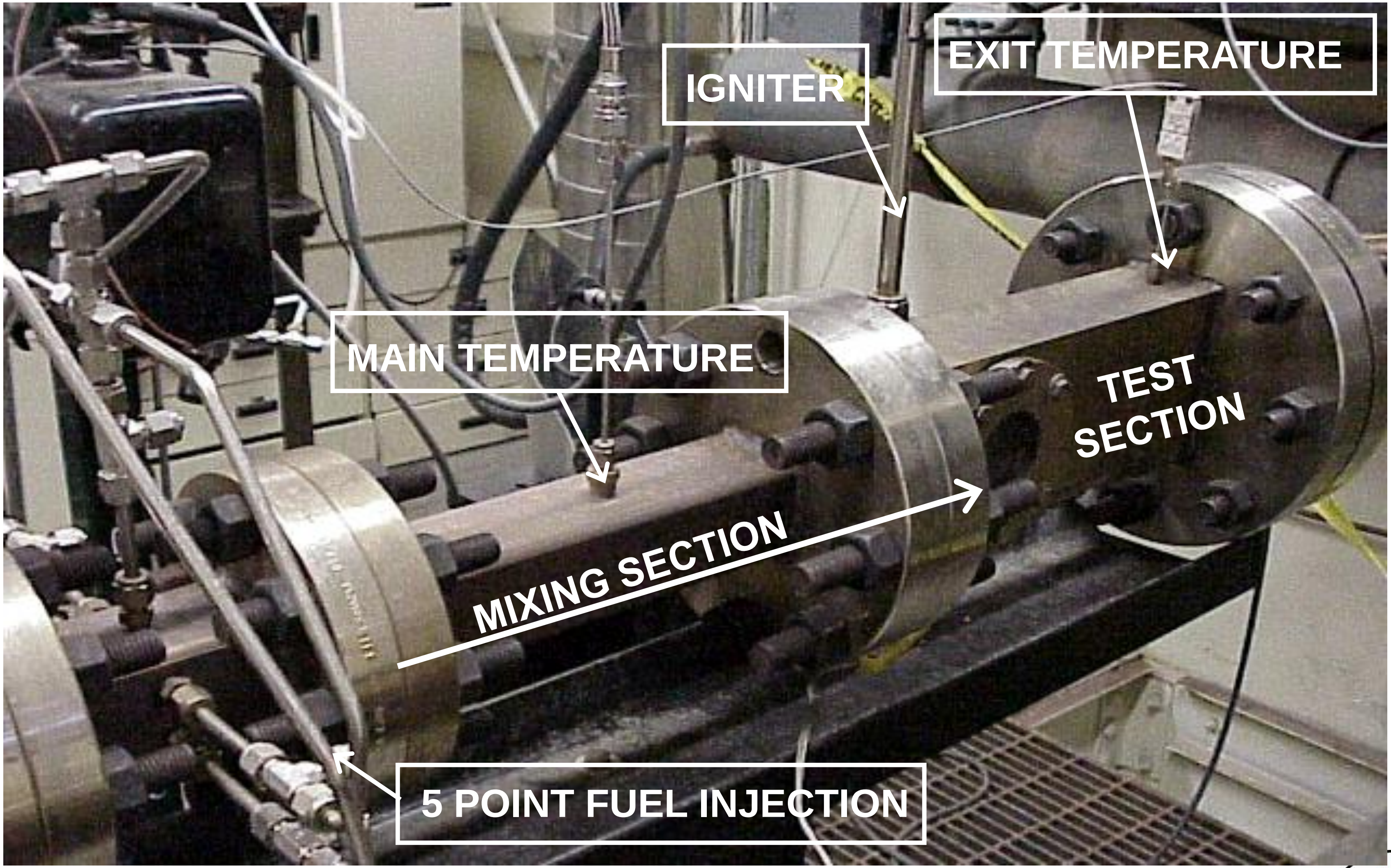


Existing Test Section available from a short duration industry study in early 2000's

--actually predated flow reactor configuration

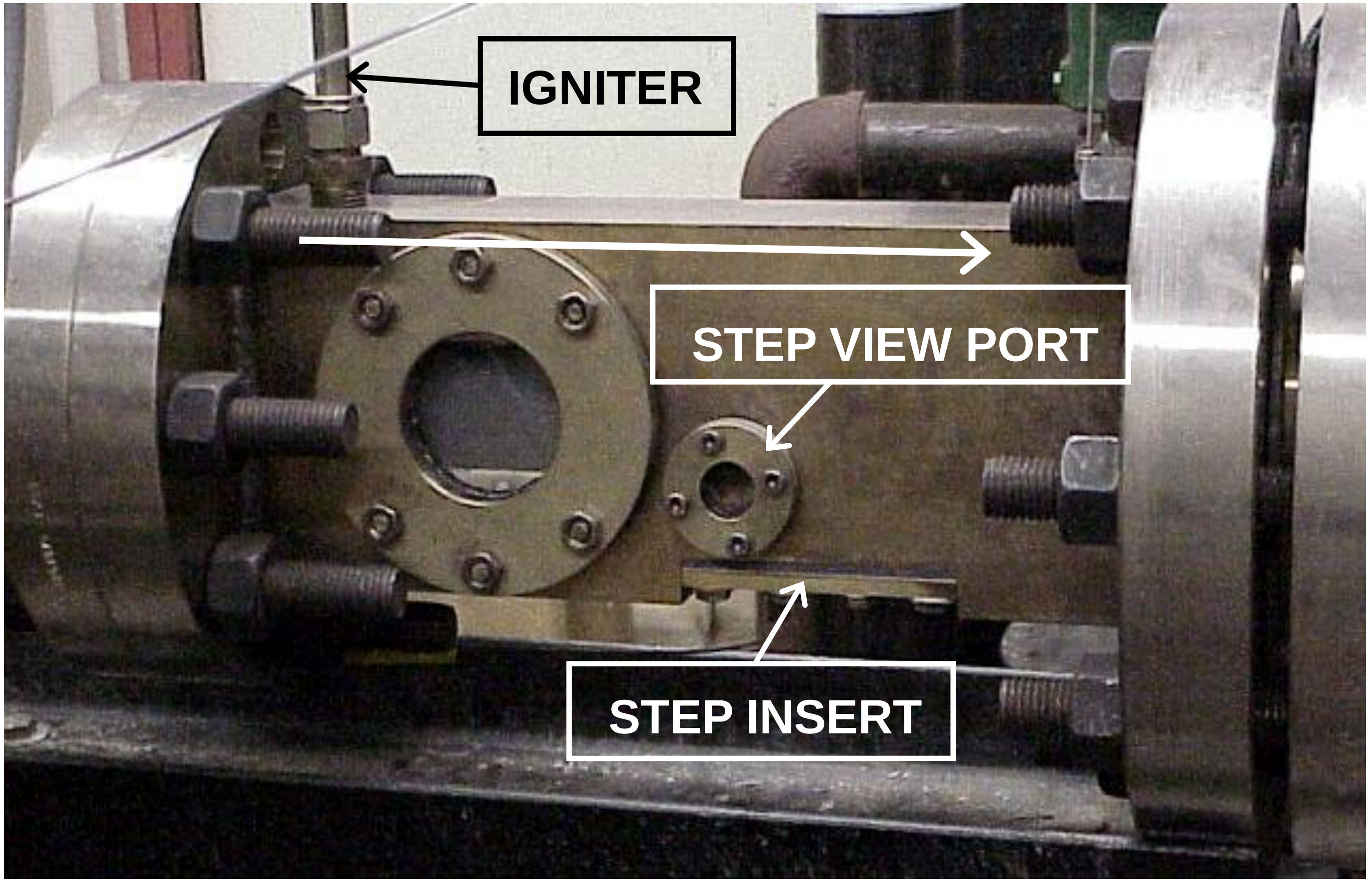
--2.5" semi-square cross section

Preparation



Legacy Test Section

Legacy Test Section



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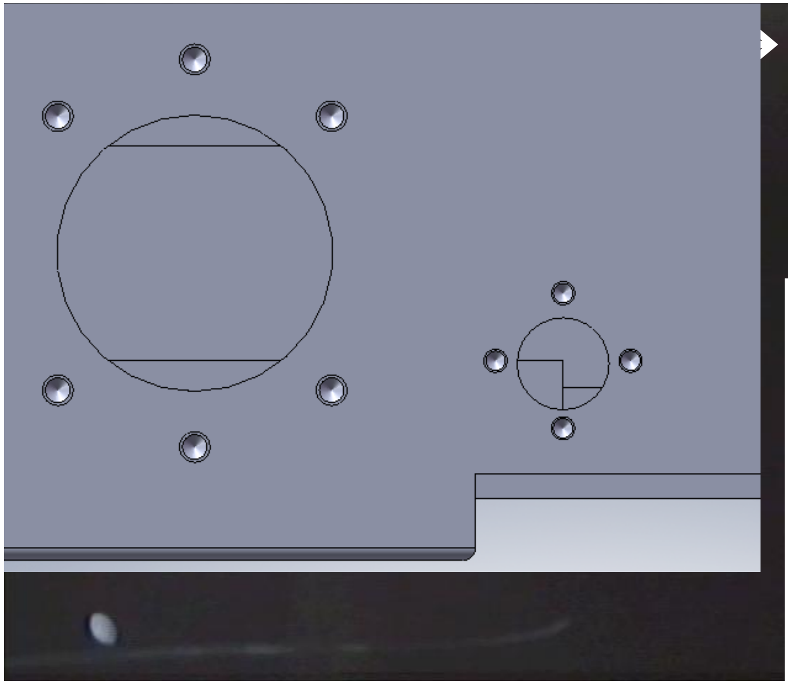
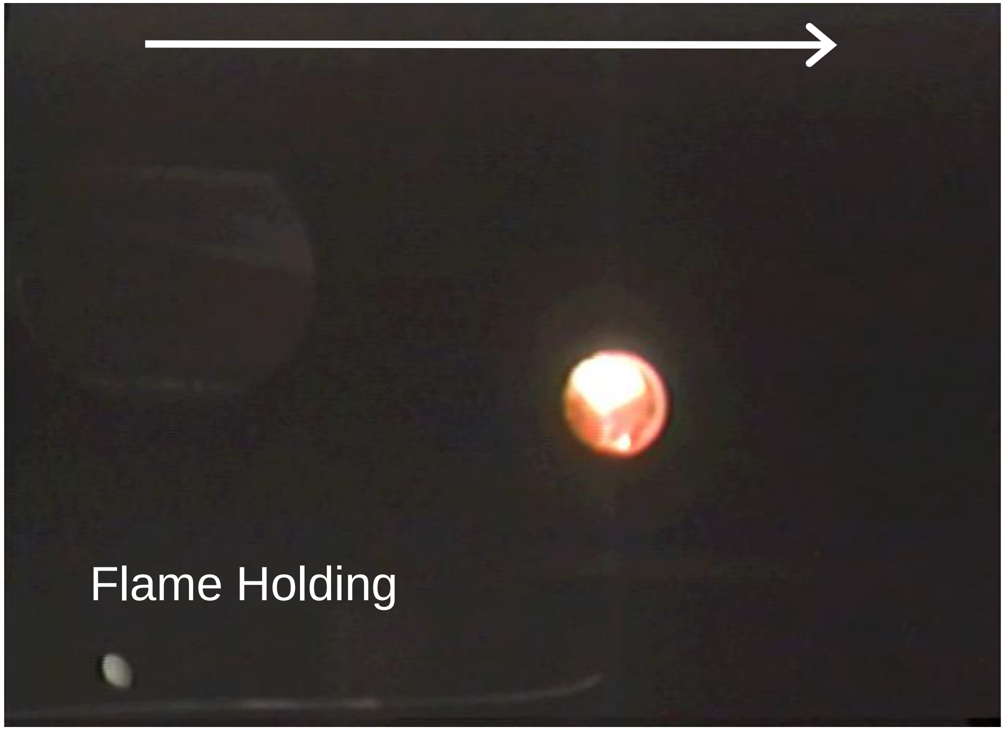
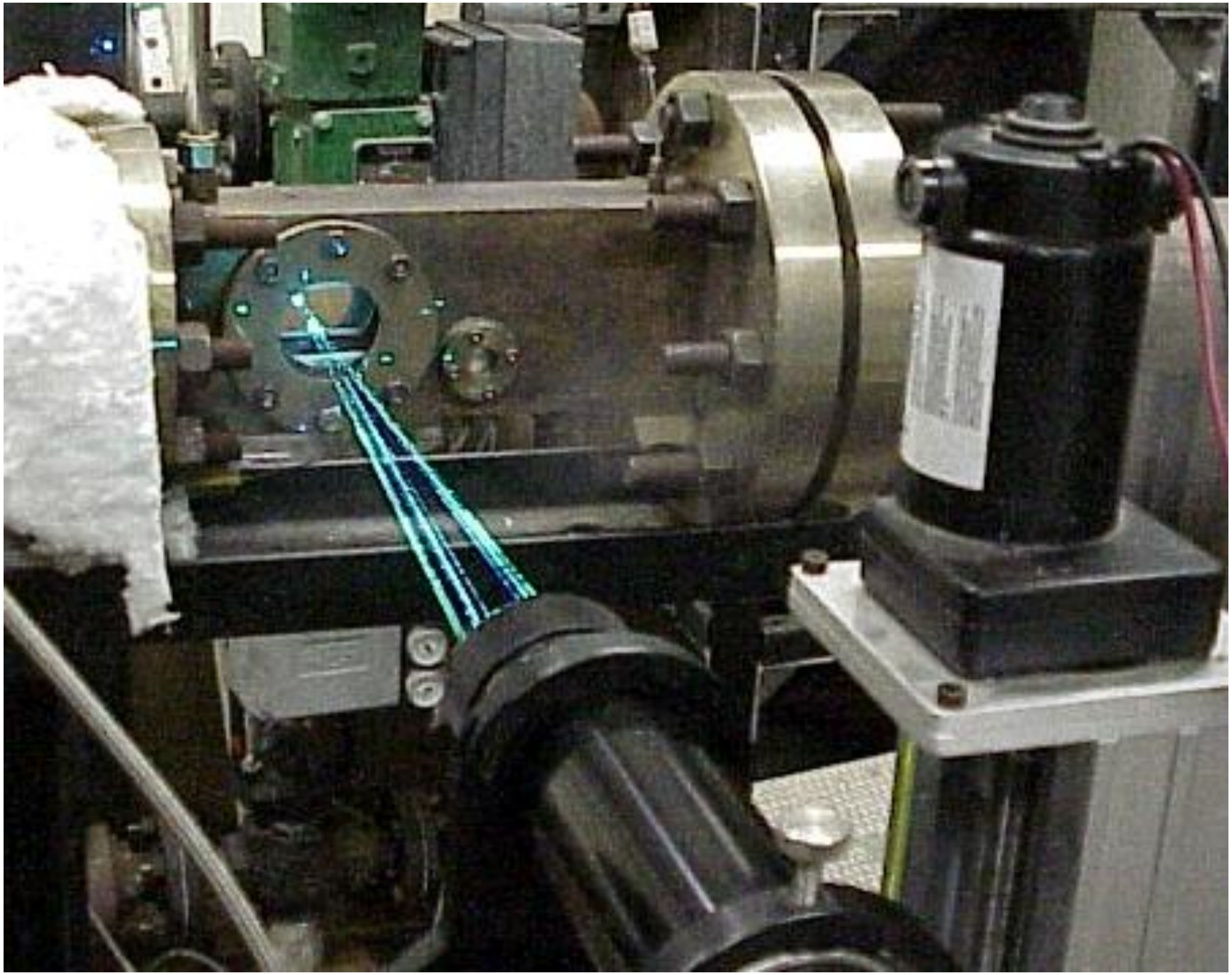


TORCH IGNITER OFF



Current Project:
High Speed OH* Imaging will be used as well
Phantom 7.2 CMOS w/ external intensifier

Velocity/Turbulence Mapping



Approach

- **Preparation**
  - **Fuel/Module Selection**
  - **Fabrication**
  - **Diagnostics / Rig Setup**
  - **Commissioning**
- **Experimental Studies**
- **Analyze and Correlate Results**

Fuel Space

Fuel Space

Table 1. Summary of Fuels of Interest (clean, dry, mole fractions).

Constituent	H_2	CO	CH_4	C_3H_8/C_4+	CO_2	N_2
Hydrogen (H2)"	100-90	0-10	0	0	0	0
Coal/Petcoke syngas ("Syngas")—nominal values shown	37	46	1	0	14	2
N2 diluted coal/petcoke syngas[2] ("Dilute Syngas")—nominal values shown	23	31	1		10	35
LNG (LNG)/Shale Gas*	0	0	90	5/5		

*For pipeline injection. For onsite use can find 50%+ ethane

Operating Conditions

Operating Conditions

Table 2. Operating Conditions and Parameter List.

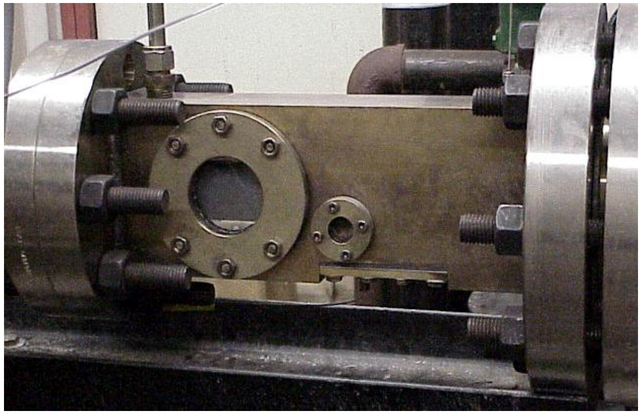
Parameter	Units	Minimum	Center	Maximum	Comment
Pressure	atm	1	7	14	
Temperature	Deg F	500	750	1000	
Turbulence Intensity	% of the Mean	5	10	15	
Overall Equivalence Ratio	None	0.6 (or low limit)	0.8	1.0	
Freestream Velocity	m/s	40	70	100	
%O2 (diluents will be CO2, N2)	% vol				

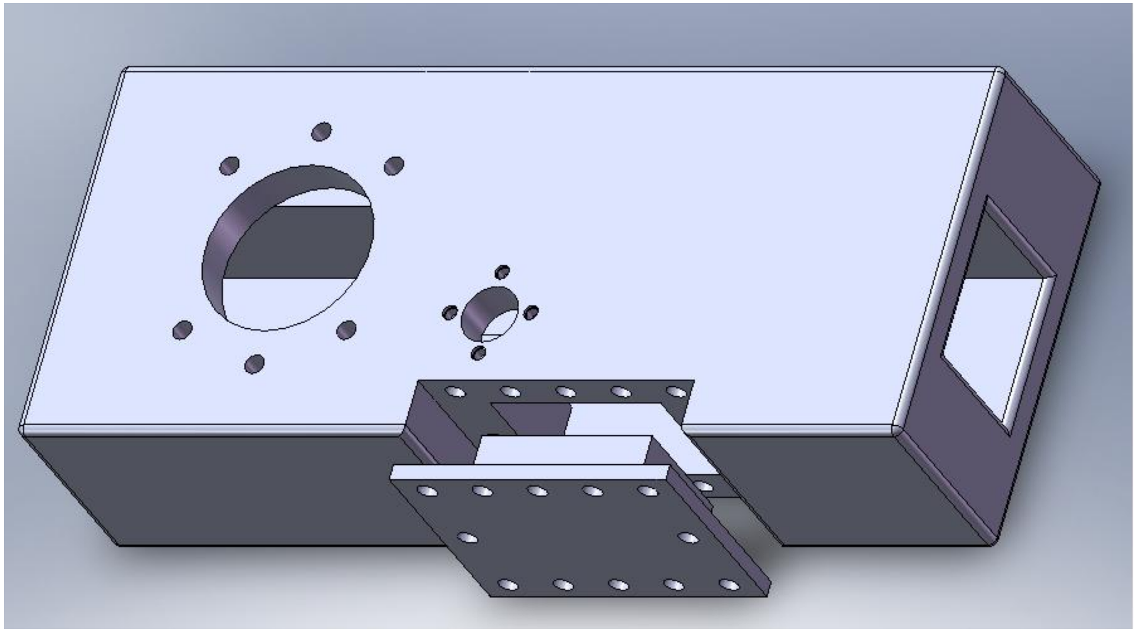
Autoignition may constrain some of this space

Test Module Selection

Test Section

- **Will consider modified version to allow top access**
- **Downstream ignition?**
- **Replace 5 point fuel injection with ignition delay venturi injector**

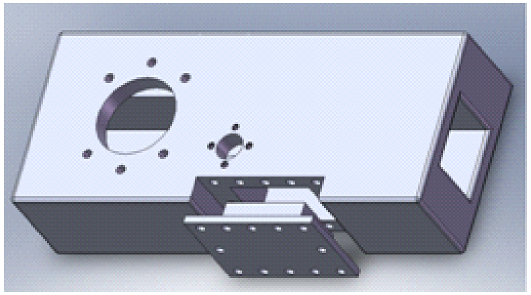




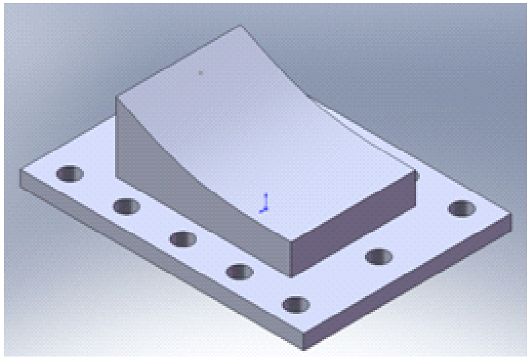
Test Module Selection

Potential Geometries

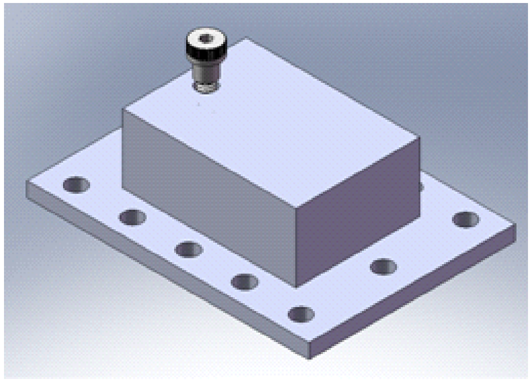
a) Baseline (step expansion



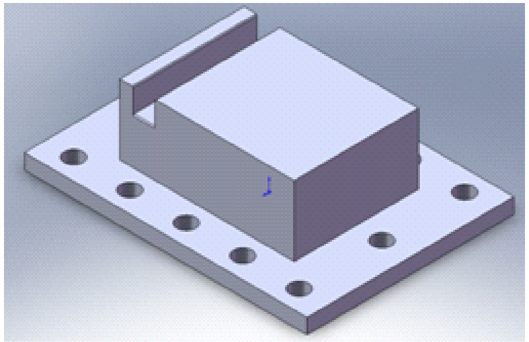
b) Angle Expansion



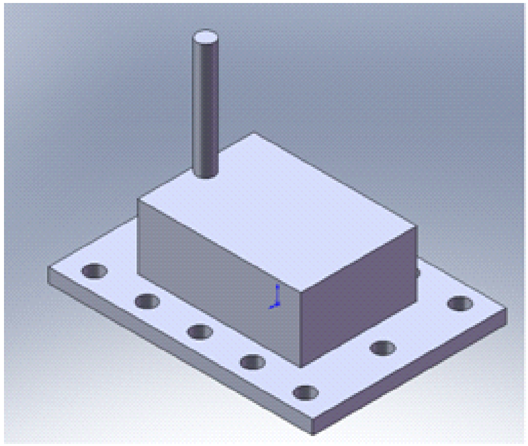
b) Bolt/Rivet



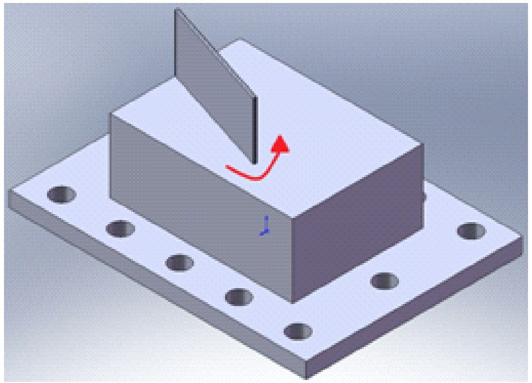
c) Channel



d) Strut

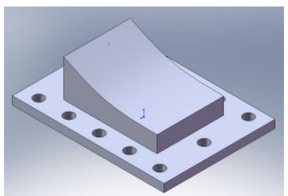


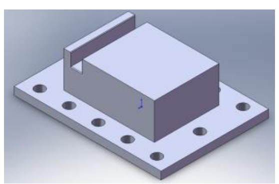
e) Vane/Strut

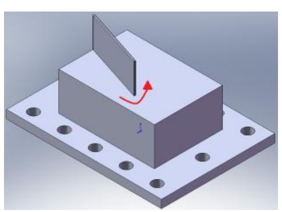


Test Module Selection

Potential Geometries







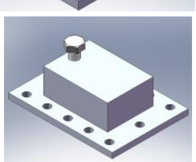


Table 3. Geometric Conditions and Parameter List.

Parameter	Units	Minimum	Maximum	Comment
Sudden Expansion (2D) Step Height	Inches	1/32	0.375	Will build 3 (legacy parts available)
Transition Angle (2D)	Deg	15	90	Will build 3 Will use 0.25" expansion height overall with different angles. 90 degree corresponds to step expansion case above
Channel (2D) Width Height	 Inches Inches	 0.125 0.125	 0.375 0.375	Will build 4
Strut/Vane (3D) Diameter Height	 Inches Inches	 0.125 0.125	 0.375 Full Length	Will build 4 Full length corresponds to extending across the test section opening to the far wall. Shape can be round or square or vane. TBD with input from OEMs
Bolt/Rivet Diameter Height	 Inches Inches	 0.125 0.125	 0.375 0.375	Will build 4

Approach

- Preparation
  - Fuel/Module Selection
  - Fabrication
  - Diagnostics / Rig Setup
  - Commissioning
- Experimental Studies
- Analyze and Correlate Results

Legacy Tests: Go/no go Findings

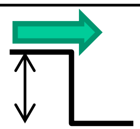
Limited studies carried out in 2002 examined "go/no go" type tests to establish max step feature for natural gas premixing to disgorge

- Only step "expansion" geometry studied
  - Test intended to evaluate→do 1/32" or 1/8" steps hold flame?
- Fuel/Velocity Distributions non-ideal (post test)

- Results can serve as a baseline for the current effort
- Also provide "seed results" for correlation evaluation
  – ANOVA

Current

Test Plan

PARAMETER	UNITS	MINIMUM	CENTER	MAXIMUM
Pressure	**atm**	**2**	**4.5**	**7**
Temperature	**deg F (K)**	**600 (588)**	**825 (714)**	**900 (755)**
Equivalence Ratio		**0.6 (or limit)**	**0.8**	**1.0**
Freestream Velocity	**ft/s (m/s)**	**100 (30.5)**	**150 (45.7)**	**200 (61.0)**
Step Heights 	**in (mm)**	**0.0313 (0.79)**	**0.125 (3.18)**	**0.250 (6.35)**

Do steps hold flame?

Test Matrix

Hold/No Hold Test

- 1 mm step didn’t hold flame
- 3.2 & 6.4 mm did
- LBO point noted as “afterthought”

LBO Point:
4 factor
2 level
Full factorial
w/Centerpoints

Allows ANOVA

Temperature degrees F	Pressure Atm	Velocity ft/s	Equiv. Ratio	Expansion inches
600	2	100	0.6	0.25"
600	2	100	0.73	0.25”
600	2	100	1	0.25"
600	2	200	0.6	0.25"
600	2	200	1	0.25"
600	7	100	0.6	0.25"
600	7	100	1	0.25"
600	7	200	0.6	0.25"
600	7	200	1	0.25"
900	2	100	0.6	0.25"
900	2	100	1	0.25"
900	2	200	0.6	0.25"
900	2	200	1	0.25"
900	7	100	0.6	0.25"
900	7	100	1	0.25"
900	7	200	0.6	0.25"
900	7	200	1	0.25"
600	2	100	0.6	0.125"
600	2	100	0.67	0.125”
600	2	100	1	0.125"
600	2	200	0.6	0.125"
600	2	200	1	0.125"
600	7	100	0.6	0.125"
600	7	100	1	0.125"
600	7	180	0.6	0.125"
600	7	180	1	0.125"
825	4.5	150	0.8	0.125"
900	2	100	0.6	0.125"
900	2	100	0.64	0.125”
900	2	100	1	0.125"
900	2	200	0.6	0.125"
900	2	200	1	0.125"
900	7	100	0.6	0.125"
900	7	100	0.67	0.125”
900	7	100	1	0.125"
900	7	200	0.6	0.125"
900	7	200	1	0.125"

Analysis of Variance

Results from ANOVA

$$WE = 0.99 - 0.00017 * Temp - 0.091 * \Pr essure - 0.0013 * Velocity + 0.0006 * \Pr essure * Velocity$$

- **Step Height not statistically significant (0.125/0.25” step)**
- **Effect of velocity depends on pressure**
  - **Low pressure, velocity has no effect**
  - **High pressure, significant velocity effect**
- **Lack of fit is significant**
  - **Indicative of non-linear behavior**
  - **Evaluation of log/ln response still indicates lack of fit**

- **Insufficient results to generate strong conclusions**
  - **Need for additional measurements**
  - **More systematic studies**

Legacy Tests: Correlation?

Limited studies carried out in 2002 examined "go/no go" type tests to establish max step feature for natural gas premixing to disgorge

- Only step "expansion" geometry studied
  - Test intended to evaluate→do 1/32" or 1/8" steps hold flame?
- Fuel/Velocity Distributions non-ideal (post test)

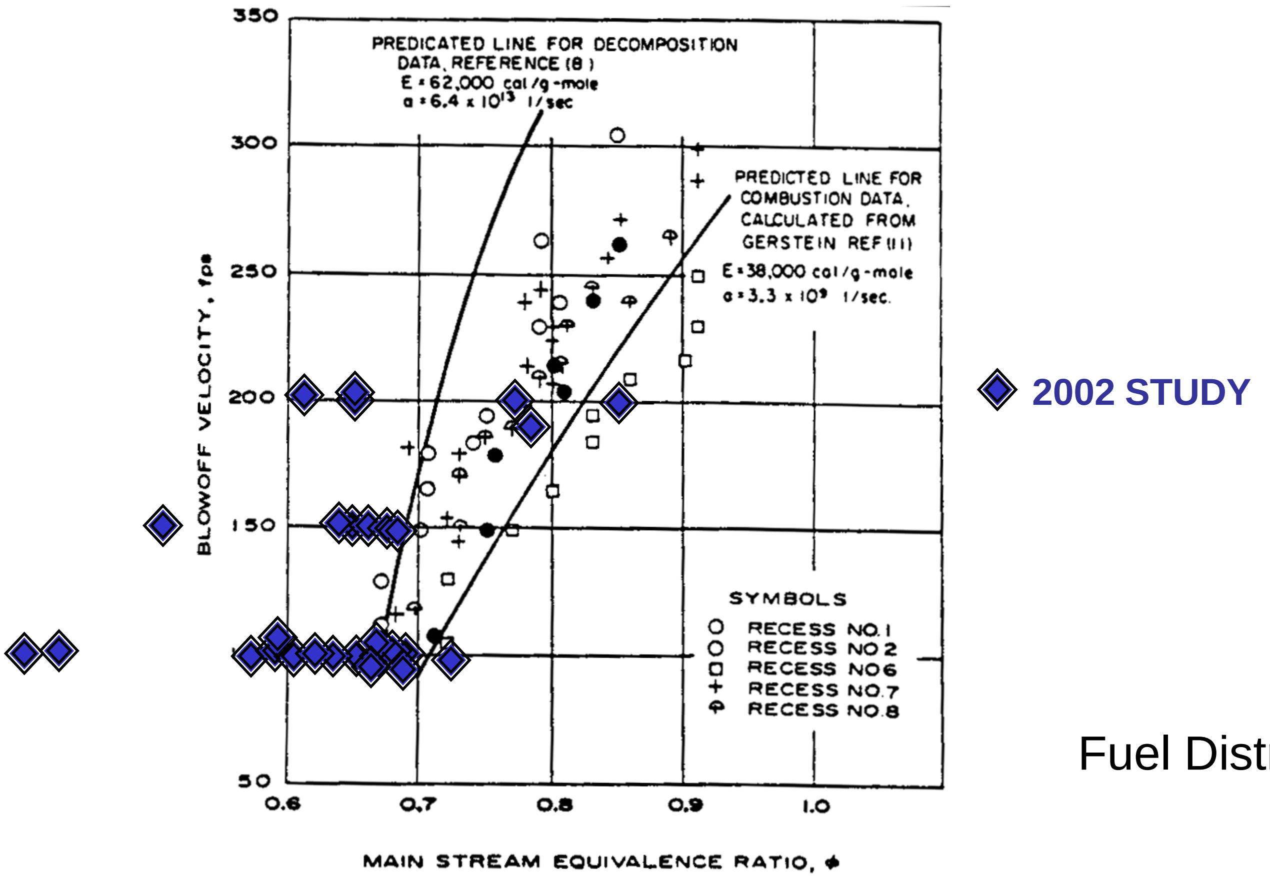
- **Results can serve as a baseline for the current effort**
- **Also provide "seed results" for correlation evaluation**
  - **e.g., vs Cambel?**

Current

Analysis

Cambel, et al. (1957, 1962)

- PROPANE
- NO TEMP VARIATION
- NO PRESSURE VARIATION



Fuel Distribution?

Legacy Tests: Correlation?

Limited studies carried out in 2002 examined “go/no go” type tests to establish max step feature for natural gas premixing to disgorge

- Only step “expansion” geometry studied
  - Test intended to evaluate→do 1/32” or 1/8” steps hold flame?
- Fuel/Velocity Distributions non-ideal (post test)

- **Results can serve as a baseline for the current effort**
- **Also provide “seed results” for correlation evaluation**
  - **e.g., Ballal and Lefebvre, (1979)**

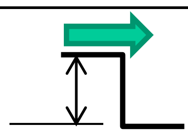
Current

$$\phi_{LBO} = \left\{ \frac{2.25\left[1 + 0.4U\left(1+u'\right)\right]}{P^{0.25} T_o e^{T_o/150} D_c \left(1 - B_g\right)} \right\}^{0.16}$$

- Essentially Damköhler scaling (reaction time/residence time)

Test Matrix

$$\phi_{LBO} = \left\{ \frac{2.25\left[1 + 0.4U(1+u')\right]}{P^{0.25} T_o e^{(T_o/150)} D_c (1 - B_g)} \right\}^{0.16}$$

PARAMETER	UNITS	MINIMUM	CENTER	MAXIMUM
Pressure	atm	2	4.5	7
Temperature	deg F (K)	600 (588)	825 (714)	900 (755)
Equivalence Ratio		0.6 (or limit)	0.8	1.0
Freestream Velocity	ft/s (m/s)	100 (30.5)	150 (45.7)	200 (61.0)
Step Heights 	in (mm)	0.0313 (0.79)	0.125 (3.18)	0.250 (6.35)

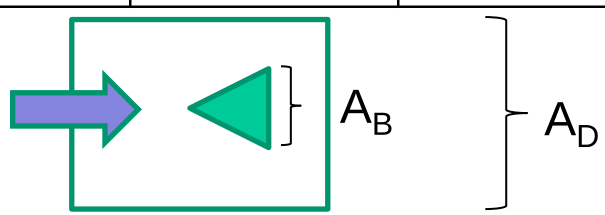
Step Heights:

B&L blockage ratio A_B/A_D: 4-34%

Current "blockage" ratio <1%

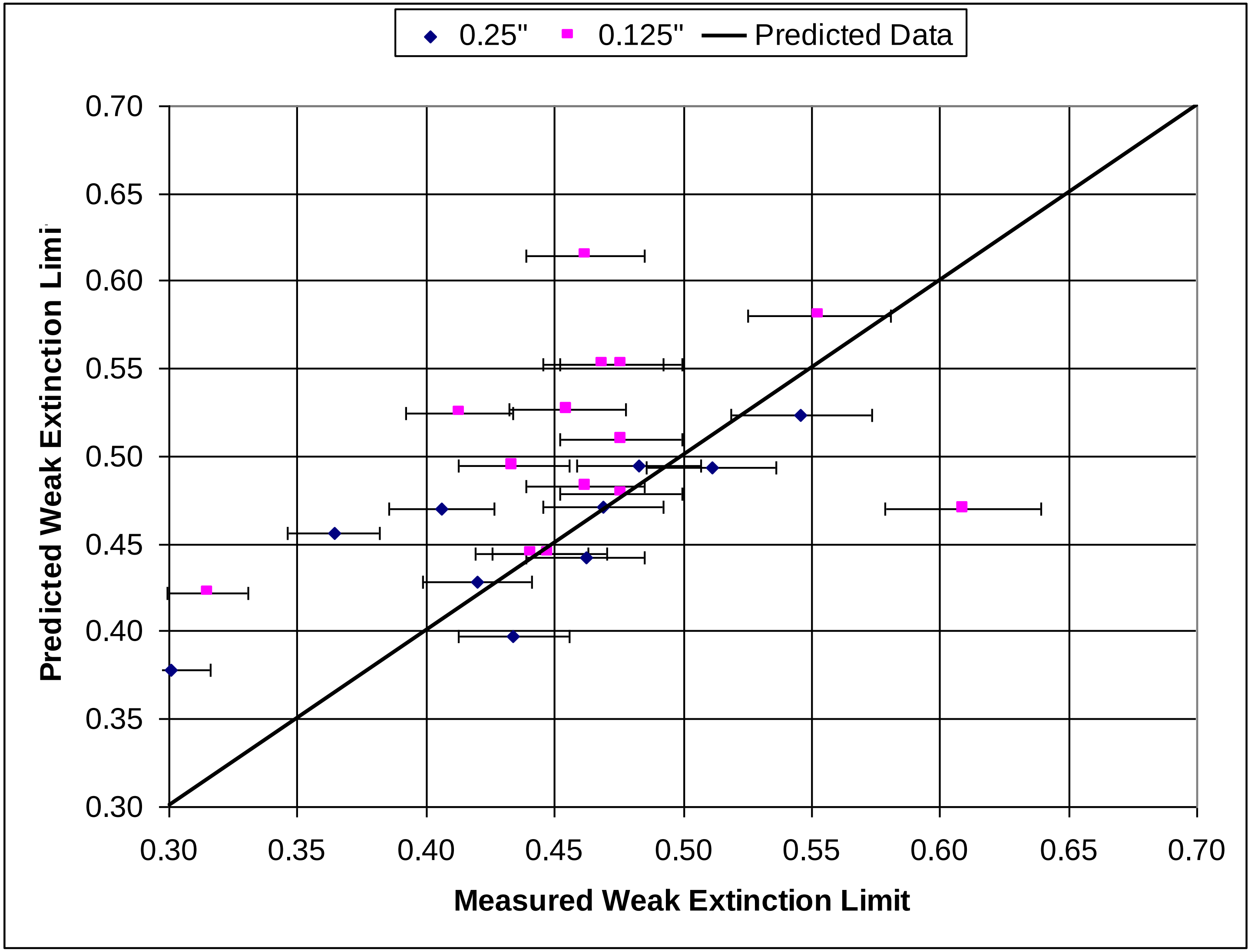
Temps: B&L 575 K max

Fuel: B&L Propane



Ballal and Lefebvre (1979)

$$\phi_{LBO} = \left\{ \frac{2.25\left[1 + 0.4U\left(1+u'\right)\right]}{P^{0.25}T_o e^{\left(T_o/150\right)} D_c \left(1 - B_g\right)} \right\}^{0.16}$$



Fuel/Air control needs improvement (already in place)

Additional Considerations

- **Consider Quench Distance within Blockage Ratio**

$$d_q = \frac{10\alpha}{S_T - 0.63u'}$$ u'>2S$_L$

Klimov expression (1983) used for S_T

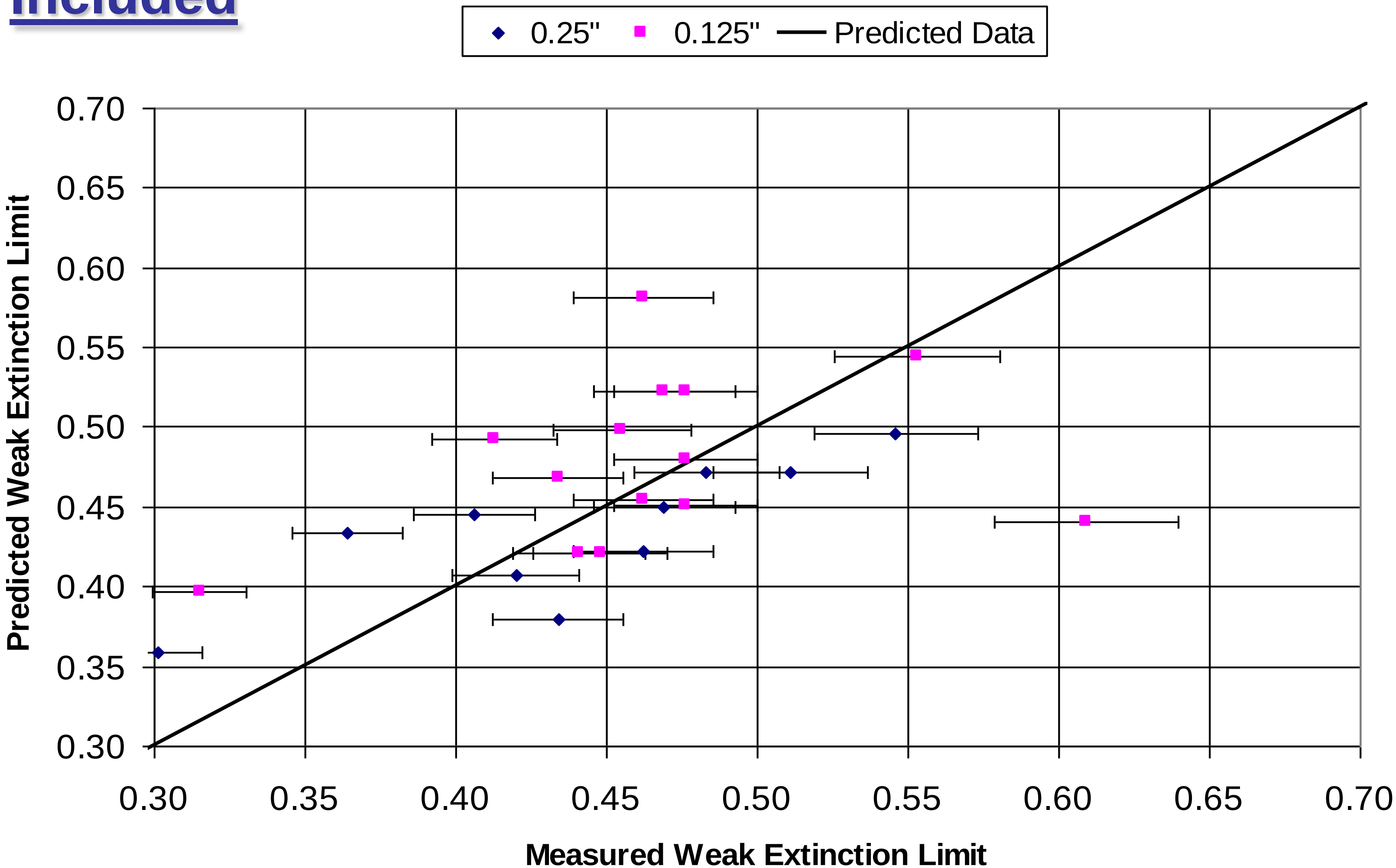
BTW--d_q ~ 0.1 mm compared to 0.8 mm for smallest step

BTW—what is S_T? (results expected from other UTSR efforts)

- **Fuel type: Reaction Order of Methane vs Propane**
  - **Pressure Dependency of Reaction Rate?**
  - **Analysis suggests P^0.3 improves fit**
  - **Lefebvre's original data suggested very small pressure dependency (unexpected)**

Additional Considerations Included

$$\phi_{LBO} = \left\{ \frac{2.25\left[1 + 0.4U\left(1+u'\right)\right]}{P^{0.3} T_o e^{\left(T_o/150\right)} D_c \left(1 - B_g\right)} \right\}^{0.16}$$



0.25” better behaved, yet still fairly poor agreement

Findings from Limited Natural Gas Data

Steps less than 0.0313” didn’t hold flame

- Quenching Limit?
- Role of conditions, fuel composition?
- Experiment Issues (fuel distribution, fuel/air control)

DOEx and Analysis of Variance

- No step effect noted (consisted w/Cambel)
  - Pressure, Velocity, Temperature, PV Interaction
  - Insufficient data to utilize ANOVA reliably

Correlation effort

- Similar trends to Cambel, but differences noted
  - Different fuels, etc
- B&L similar trends, but not good agreement
  - Different fuels, temperatures
  - Large bluff body vs small wall features

Research Questions remain!

Current Project

Task Description	Year 1		Year 2		Year 3	
	M1	M7	M13	M19	M25	M31
Task 1—Project Management and Planning*		*	*	*		
Task 2—Preparation -Task 2.1—Fuel/Module Selection -Task 2.2—Fabrication -Task 2.3—Diagnostics/Rig Setup -Task 2.4--Commissioning						
Task 3—Experimental Studies -Phase I -Phase II						
Task 4—Analysis and Model Development						

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