Oxygen-Rich Combustion Experiments in a LOX/GH_2 Uni-element Rocket

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Background

Combustion characteristics of a LOX/GH_2 swirl coaxial injector element have been examined up to very high oxidizer to fuel ratios in a research rocket chamber at Penn State University's Cryogenic Combustion Lab. The single-element tests demonstrate that, for injector element flowrates comparable to those of booster engine injectors, ignition, stable combustion, and good performance can be achieved with LOX at O/F ratios as high as 170.

Operation of injectors at such high O/F ratios is a highly desirable element of candidate cryogenic propulsion systems for next-generation Reusable Launch Vehicles (RLV). Oxygen-rich preburners, supplying low temperature exhaust gases to the turbine drives, have the potential to minimize cost, weight, and operational complexity of advanced rocket engines. Fundamental data at the single-element level, such as that reported here, is a component of an industry-wide oxygen-rich combustion technology program for RLV propulsion. Recent progress is summarized in this presentation.

Research Objectives

Research efforts are directed towards understanding specific technical issues that must be resolved to minimize the risk and cost associated with developing oxygen-rich rocket preburners. The experiments concentrate on hot-fire uni-element tests to demonstrate concepts which can be incorporated into hardware design and development. Two concepts under consideration are direct injection of propellants at high O/F, and stoichiometric injection followed by downstream injection of LOX to achieve the high O/F. The specific results given here address the performance, ignition, combustion stability, and wall heat transfer aspects of a direct-injection swirl coaxial element design operating at high O/F.

Current Progress

Experiments with direct-injection at high O/F have been conducted in an optically-accessible uni-element rocket test chamber of 2 inch square cross-section (1.1 ft. length) with LOX/GH_2 propellants. A swirl coaxial injector element, characterized under both cold-flow and hot-fire, was used to atomize the LOX. LOX flowrates were held constant in the experiments while O/F ratio was achieved by varying the hydrogen fuel flowrate. A gaseous hydrogen/oxygen torch was used to ignite the main flow.

A series of experiments has been completed where O/F ratio was varied from 5 to 170, while simultaneous measurements were made of high frequency pressure oscillations and wall heat transfer. Chamber pressures for this series were nominally 300 psia, and data was obtained at both upstream and downstream locations within the rocket chamber. The results show that wall heat transfer is greatly reduced for high O/F combustion. Pressure oscillations are also at a low level, approximately 1% of chamber pressure, for the entire range of O/F.

Further characterization of the direct-injection high O/F scheme is planned, and will involve non-intrusive measurement of spray penetration and the spray flame temperature.

Acknowledgment

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OXYGEN-RICH COMBUSTION EXPERIMENTS IN A LOX/GH_2 UNI-ELEMENT ROCKET

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PENNSTATE

Department of Mechanical Engineering
and
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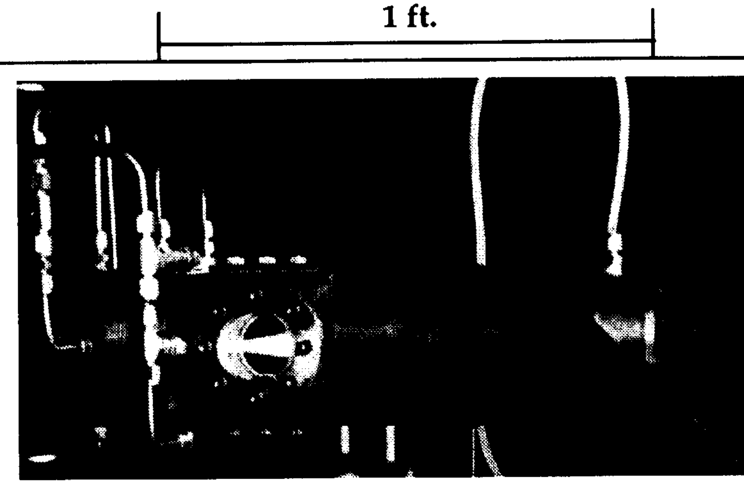
  - Penn State University

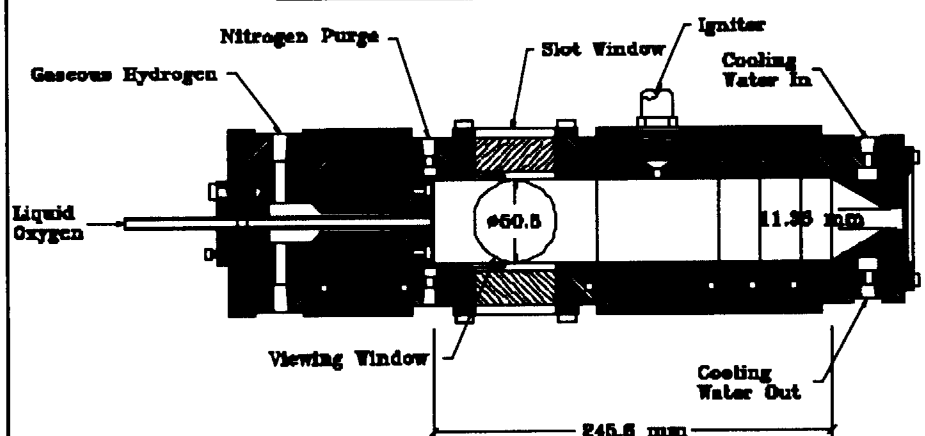
OPTICALLY ACCESSIBLE ROCKET CHAMBER

- Heat-Sink Copper Chamber
- Modular / Interchangeable Chamber Sections
- 51 x 51 mm Cross-Section (2 in. square)
- 51 mm (2 in.) Round Viewing Windows
- 51 mm (2 in.) long Slot Windows on top/bottom
- Gaseous H_2/O_2 Torch Ignitor

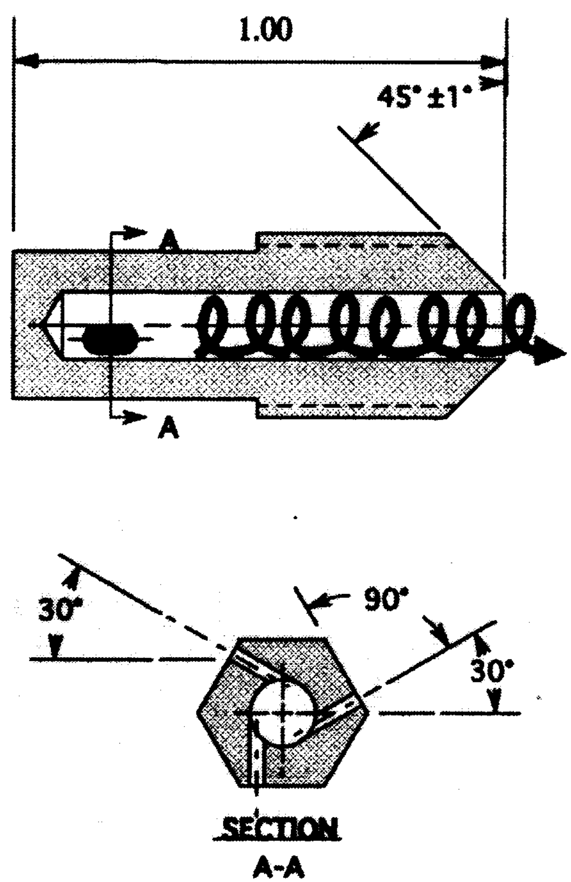
Penn State

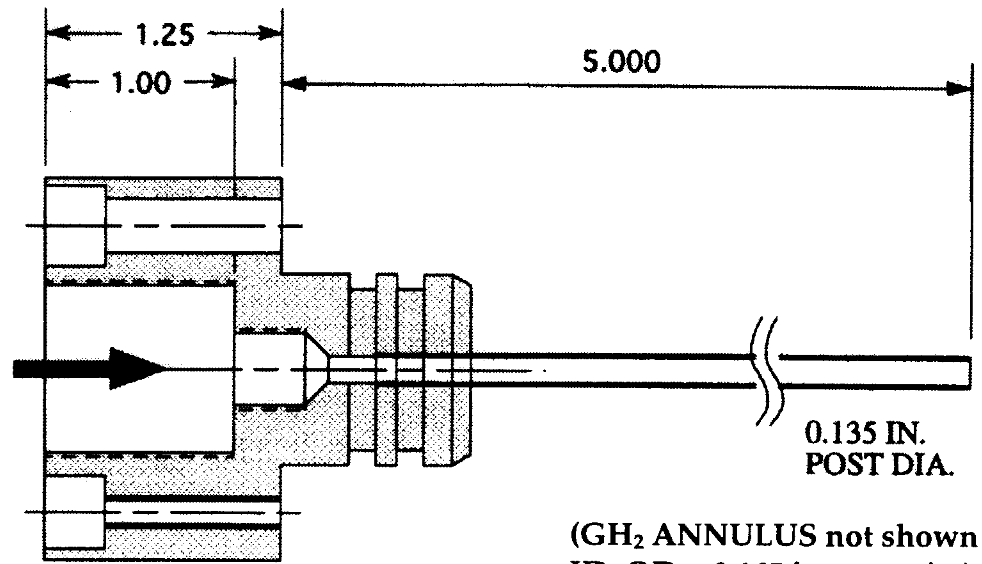
Uni-Element Rocket Chamber





SWIRL COAXIAL INJECTOR





(GH$_2$ ANNULUS not shown
ID, OD = 0.165 in., 0.280 in.)

- **LOX/GH$_2$ Injector Design is Based on Industry Practice**
  - **2 Injectors (0.135 in. & 0.277 in. POST ID)**
  - **Injector shown is similar to RL10A-4-1**
  - **Design Derived from STME Studies by Aerojet, Pratt & Whitney, MSFC**

Ref.: Rahman et al. '95, AIAA Paper No. 0381

OBJECTIVE & MOTIVATION

- **Augment Limited Experimental Data Base on Oxygen-Rich Combustion**
  - Demonstrate Ignition/Combustion
  - Identify High O/F Limit of Combustion

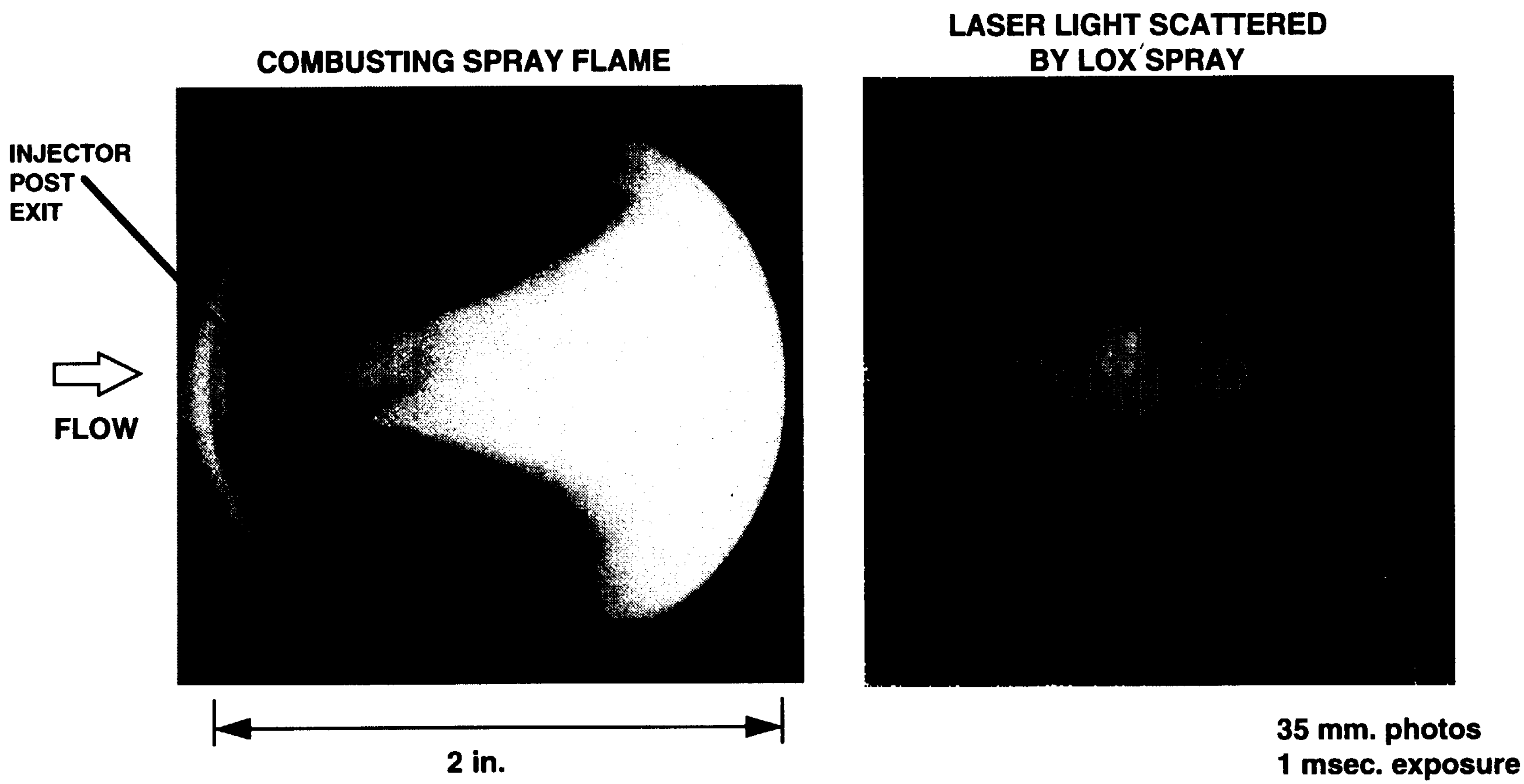
- **RLV Propulsion Technology Issues to be Addressed**
  - LOX/GH_2 Preburner Operation at High O/F
  - Full Face Injection vs. Stoich. Injection + Dilution

OVERVIEW & STATUS

- Hot-Fire with LOX/GH_2 Swirl Coaxial Injector (0.135 in. POST ID)
  - LOX Flowrates 0.25 - 0.4 lbm/s
  - P_c 150 - 500 psia
  - O/F 5 - 170
- High O/F Studies (P_c = 300 psia nom.)
  - Meaurements Completed
    - » Chamber Wall Heat Transfer
    - » High Frequency Pressure
    - » C* Efficiency
- High O/F Studies (P_c = 800 psia nom.)
  - Repeat Above Measurements
  - Testing in Progress

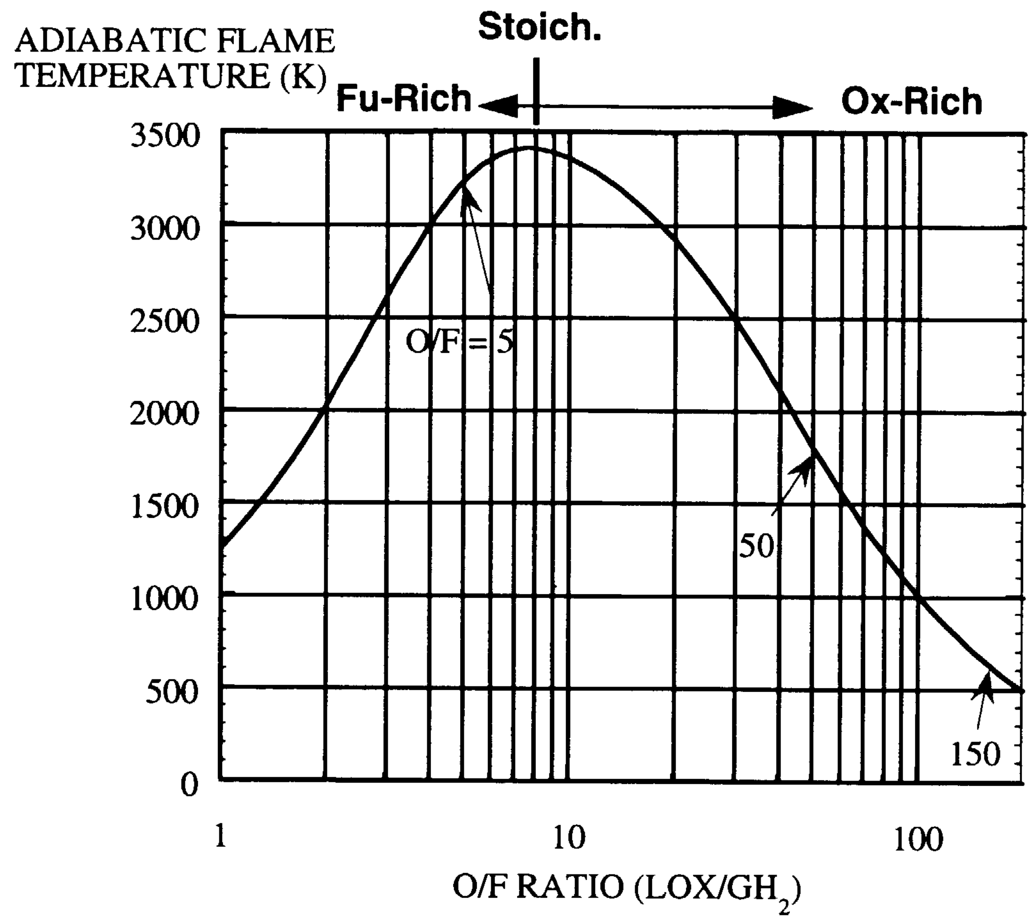
[redacted] HOT-FIRE ... FLOWFIELD

LOX/GH_2, O/F = 5.7, P_c = 440 psia



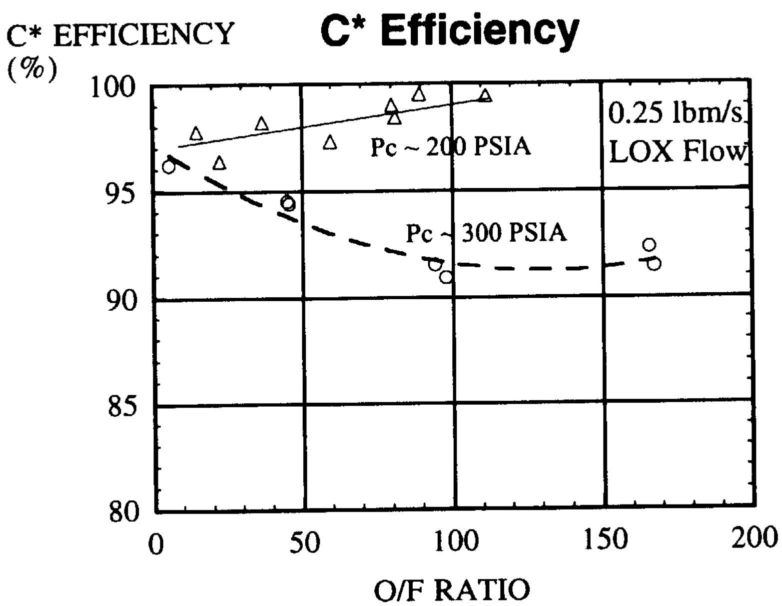
- **Conical Flame Zone Attached to LOX Post (left)**
- **Laser-Light Scattered by LOX Drops in Flame (right)**

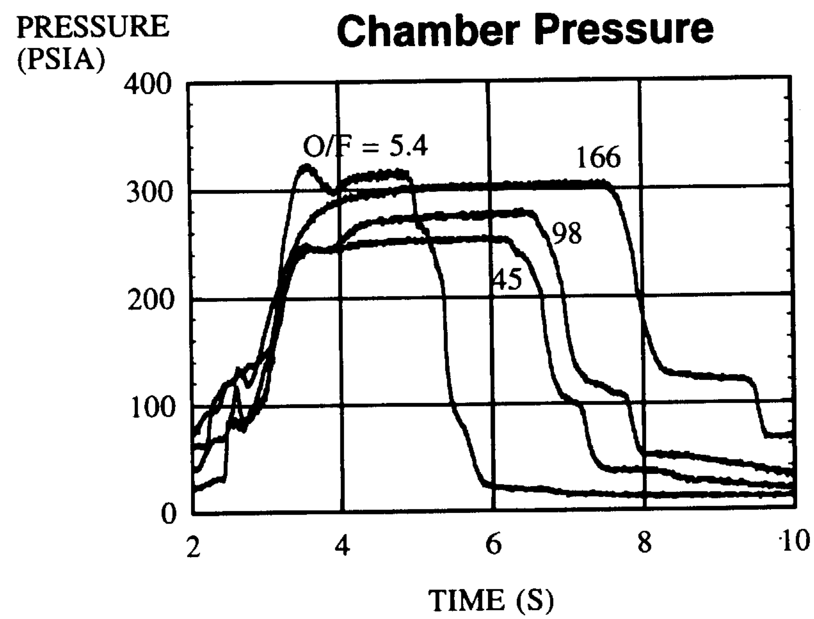
HIGH O/F COMBUSTION



- **Adiabatic Flame Temperature Decreases with O/F Ratio**

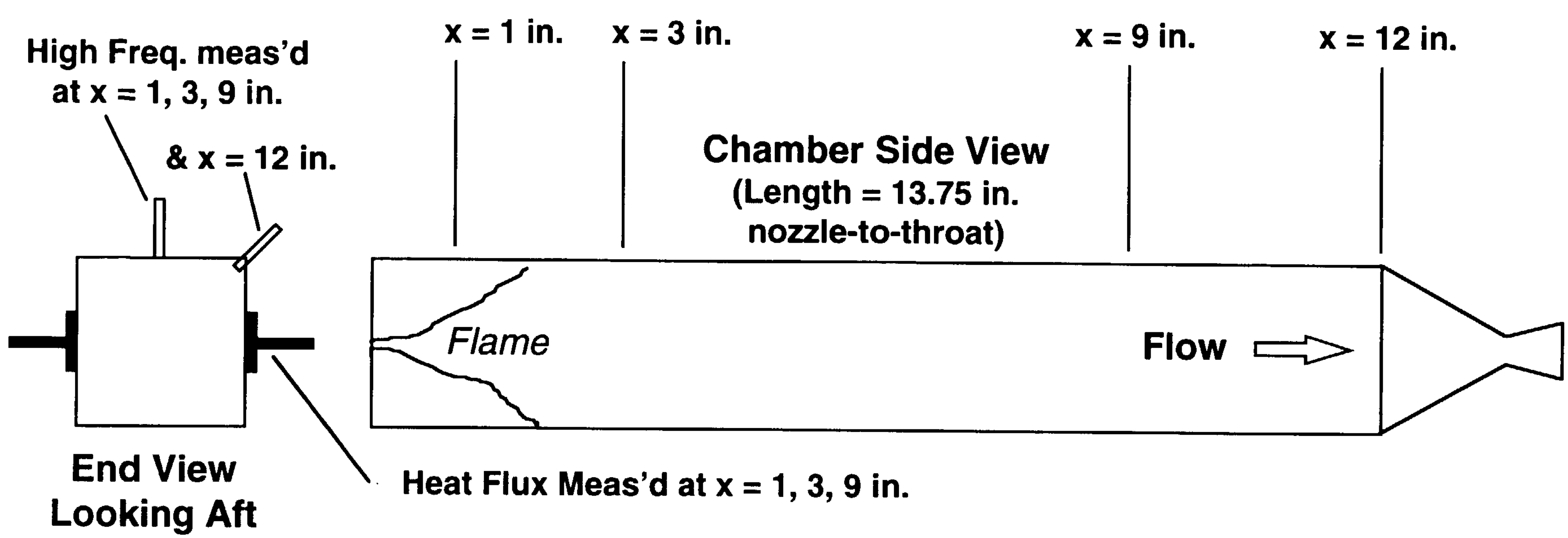
[redacted] C* EFFICIENCY AT HIGH O/F





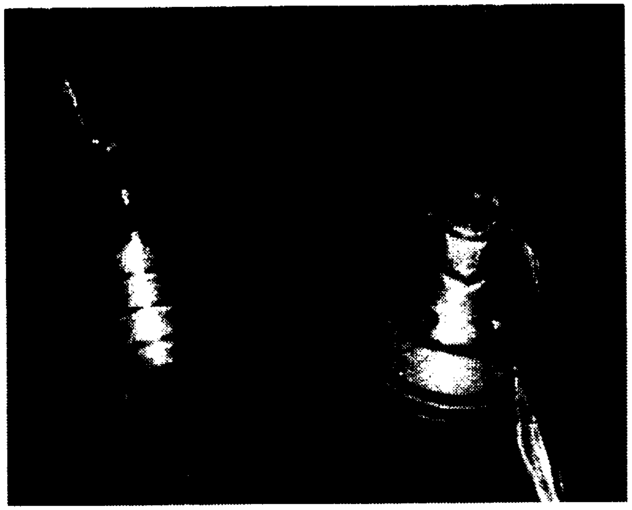
- **Tests Demonstrate Ignition/Combustion for O/F Ratio = 5 to 170**
  - **P_c = 200 - 300 psia**
  - **Swirl Coaxial Injector**
  - **LOX/GH_2 Propellants**
  - **0.25 lbm/s LOX Flow**
  - **Some Tests with Larger LOX Injector**
  - **93% C* Efficiency for (O/F = 125 - 140, LOX Flow = 0.9 lbm/s)**

[redacted] TEST INSTRUMENTATION

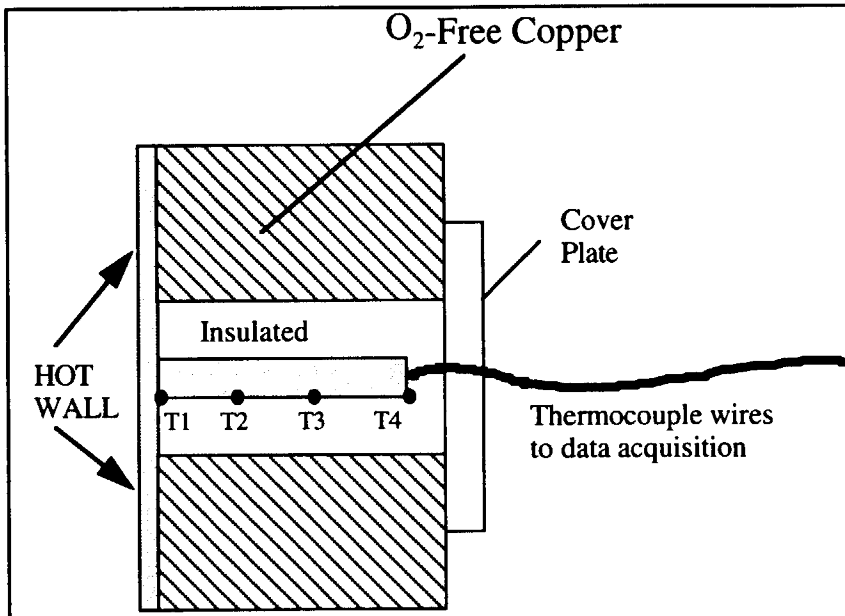


- 2 Heat Flux Gauges
- 2 High Freq. Pressure Gauges (PCB Model 113A24)
- 2 Chamber Pressure Gauges (Setra Model 204)
- Flow Metering with Calibrated Venturi Orifices

HEAT FLUX MEASUREMENT



- 2 Heat Flux Gauges Used
  - On Opposing Sidewalls of Rocket
  - Heat Xfer. Computed from Temps. T1, T2, T3, T4
  - Technique by NASA LeRC, Ref: Liebert '88, NASA-TP-2840
- Transient Heat Flux Obtained



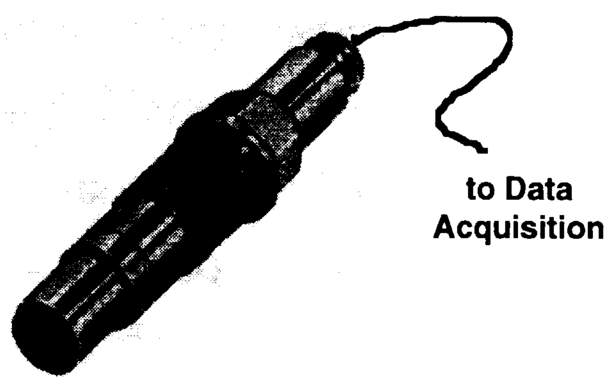
Thermocouple Locations (in-depth)

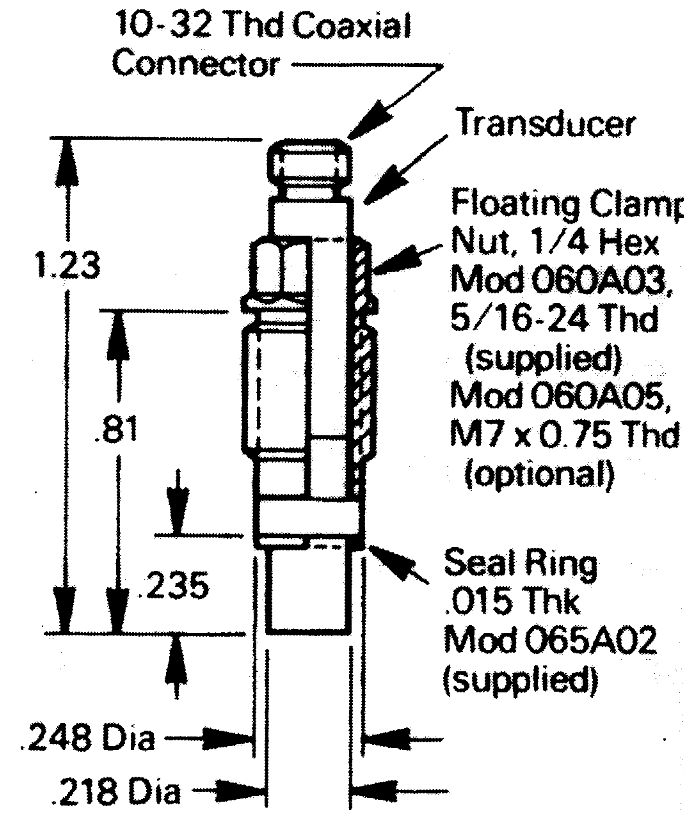
Gauge A		Gauge B	
T1	0.062 in.	T1	0.100 in.
T2	0.322 in.	T2	0.335 in.
T3	0.583 in.	T3	0.600 in.
T4	0.875 in.	T4	0.875 in.

Chromel-Alumel
Type K

HIGH-FREQUENCY PRESSURE GAUGE

- **PCB Gauge Model 113A24**
  (500 kHz Natural Freq., 1 μsec response)
- **50 kHz Sampling Employed**
- **0.02 psi Resolution**
- **Gauge Mounted almost flush with Chamber Inner Wall**





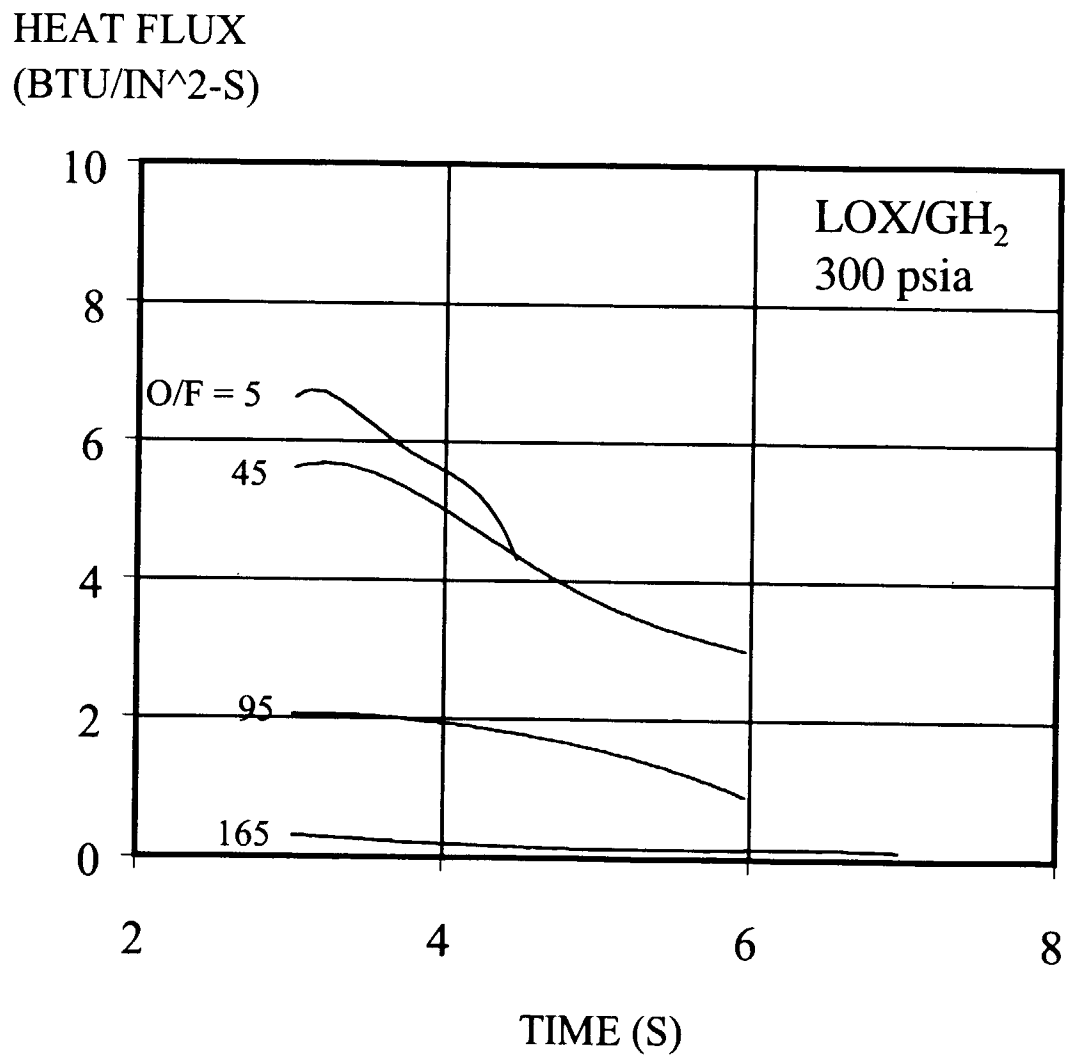
TRANSDUCER ASSEMBLY
(As Supplied)

HIGH O/F HOT-FIRE MATRIX

LOX Flow (lbm/s)	Hydrogen Flow (lbm/s)	O/F Ratio	Chamber Pressure (psia)	Estimated Flame Temp. (deg R)	C*-Eff. (%)	Instrument Locations: Heat Flux Gauges A & B			Instrument Locations: High Frequency Pressure Xdcrs.			
						x = 1in.	x = 3 in.	x = 9 in.	x = 1in.	x = 3 in.	x = 9 in.	x = 12 in.
0.256	0.04197	**6.1**	295	6160	95.6	x			x			x
0.256	0.00552	**46.4**	262	3435	94.9	x			x			
0.26	0.00252	**103**	249	1765	84.3	x			x			
0.261	0.00157	**166**	301	1100	90.3	x			x			
0.258	0.04859	**5.31**	336	6010	100		x			x		x
0.257	0.00552	**46.6**	258	3425	93.2		x			x		
0.257	0.00266	**96.5**	277	1880	91.5		x			x		
0.257	0.00153	**168**	302	1085	92.7		x			x		
0.259	0.04868	**5.32**	315	6015	95.7			x			x	x
0.246	0.00557	**44.2**	254	3555	93.5			x			x	
0.257	0.00271	**94.8**	264	1910	86.5			x			x	
0.265	0.00155	**171**	308	1060	92.7			x			x	

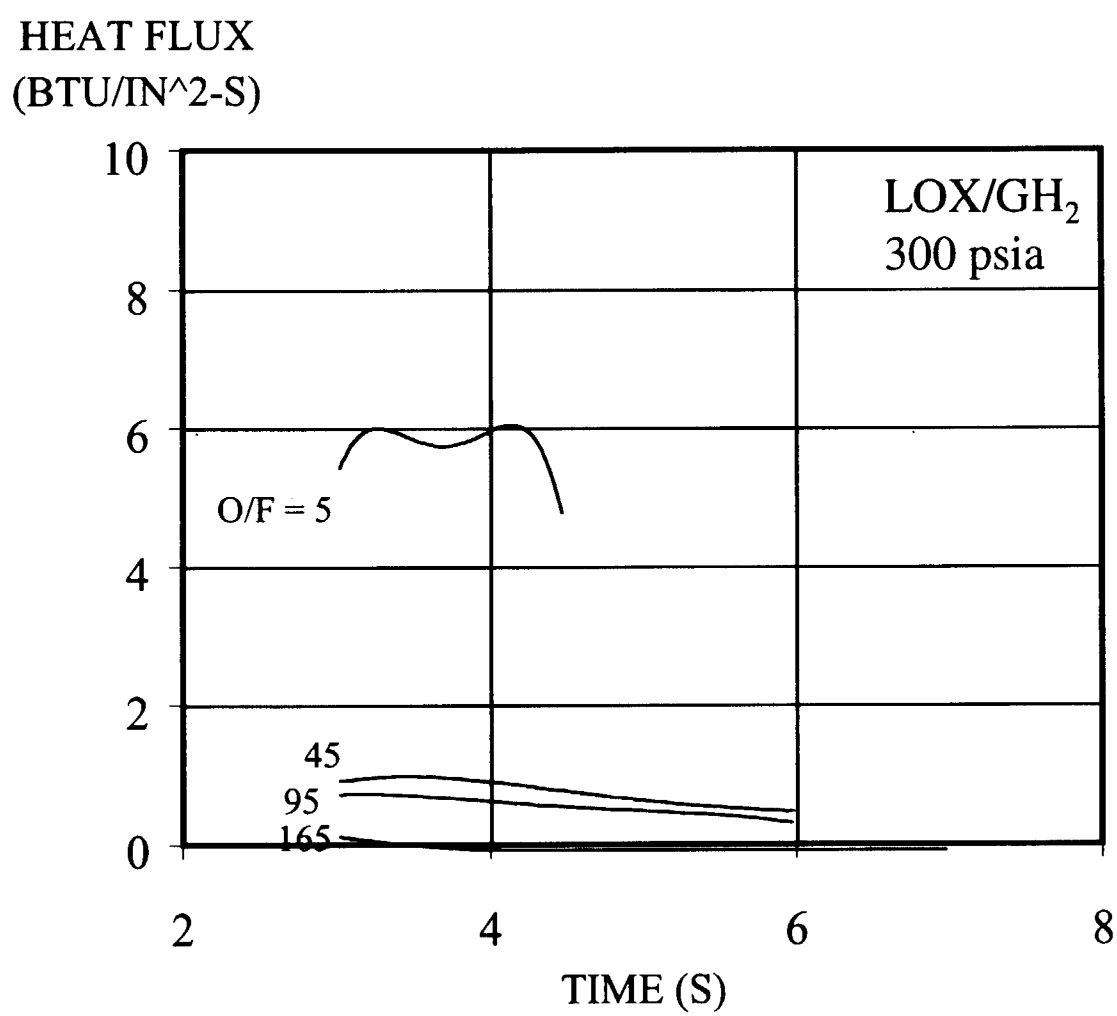
- **LOX Flowrate Held Constant at 0.25 lbm/s**
- **GH_2 Flow Varied to Achieve Ox-Rich Conditions**

WALL HEAT FLUX ... x = 1 in.

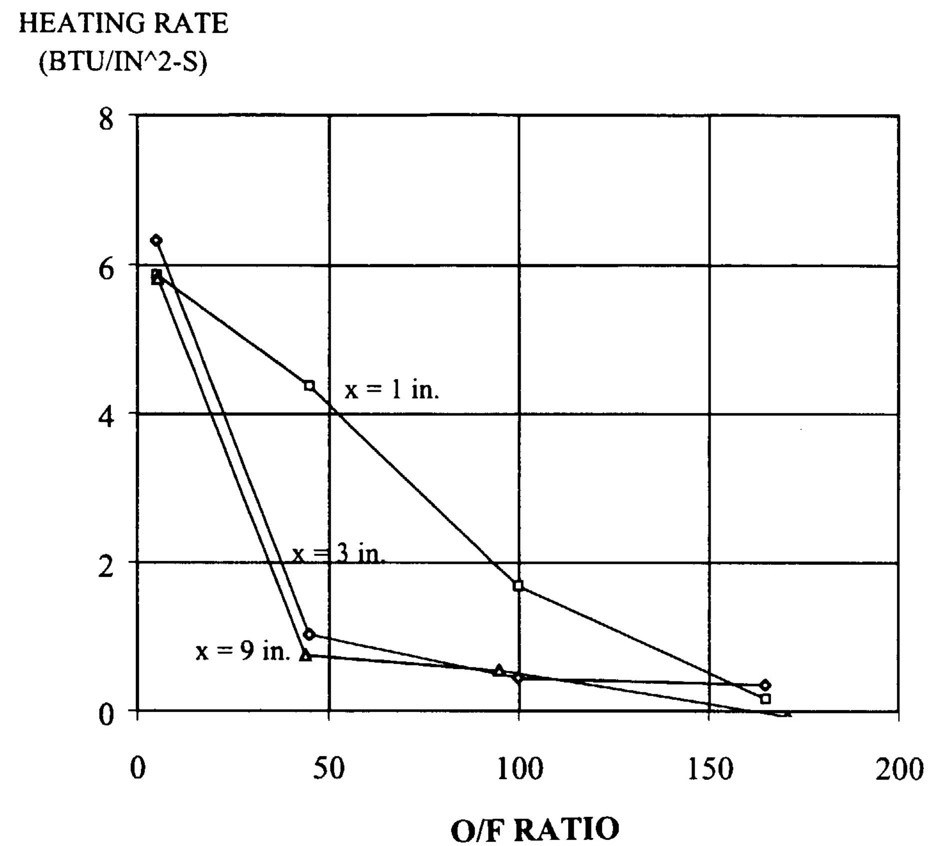


Data is for Steady-State firing period (ignition/shutdown transients excluded)

WALL HEAT FLUX ... x = 9 in.



WALL HEAT FLUX vs. O/F



Data Points are Time-Average Values of Heat Flux

- **Heat Flux Decreases with Increasing O/F**
- **Near-Injector Heating Significantly Greater (O/F of 45, 100)**

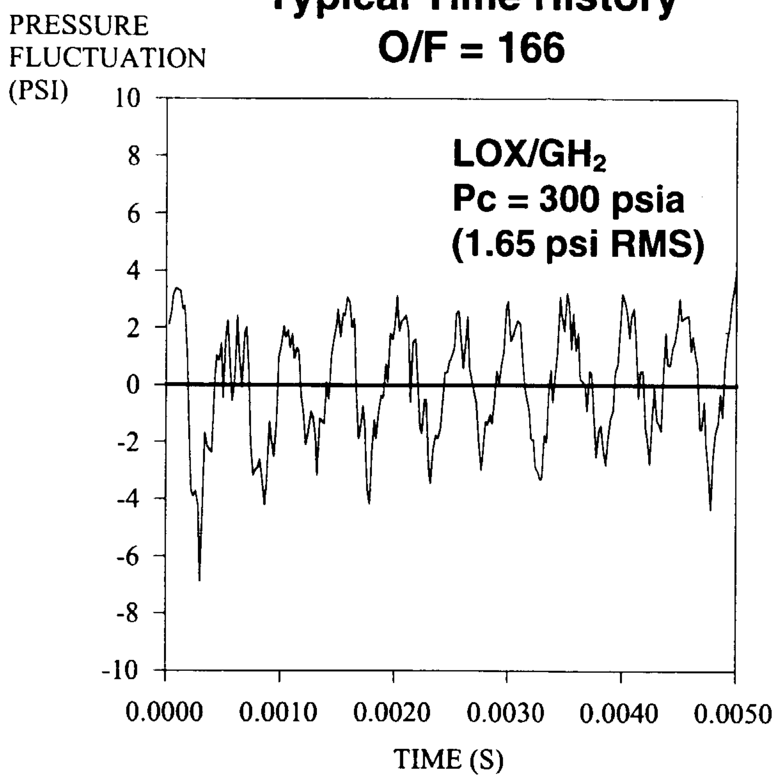
HEAT FLUX ... Other Work

	PENN STATE	AEROJET ('73)	PRATT & WHITNEY ('91)
INJECTOR	Swirl Coax 1 Element	Swirl Coax 42 Elems.	Swirl Coax 60 Elems.
PROPELLANTS & O/F	LOX/GH_2 5.3	GOX/GH_2 4	LOX/GH_2 6
LOX FLOW (lbm/s)	0.25	n/a	1
P_c (psia)	300	300	1780
HEAT FLUX (Btu/in^2-s)	6	7.5	25

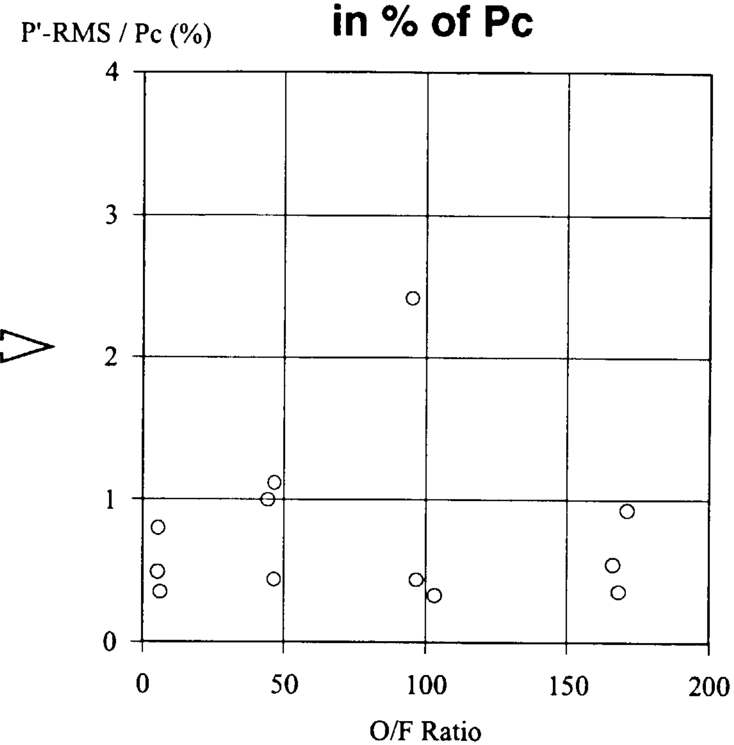
- Chamber Heat Flux Compared to Other Work
  - Compares to Aerojet Result
  - Penn State Heat Flux Scales With Element Flowrate to 18 Btu/in^2-s for 1 lbm/s Element (25 Btu/in^2-s for P&W)

HIGH FREQ. PRESSURE DATA

Typical Time History
O/F = 166



Pressure Fluctuation
in % of Pc



- **Low-Level Pressure Fluctuations Observed for all O/F**
  - **RMS Less Than 1% of Pc**
  - **Longitudinal Modes (Low Freq. < 3000 Hz Typ.)**

CHAMBER RESONANT FREQS.

O/F Ratio	P'-rms / Pc (%)	Resonant Frequency Observed (Hz) at Different Positions				Predicted Freq. (Hz)
		x = 1 in.	x = 3 in.	x = 9 in.	x = 12 in.	
6.1	0.35	6476			none	2360 (1L)
5.31	0.49		6534		-	7140 (3L)
5.32	0.80			**6580**	-	
46.4	0.44	1279			1279	
46.6	1.12		**1291**		-	1240 (1L)
44.2	1.00			**1309**	-	
103	0.33	931			931	
96.5	0.44		1154		1154	910 (1L)
94.8	**2.42**			**1740, 1975, 5081**	-	
166	0.55	2032			2032	690 (1L)
168	0.36		2029		-	2070 (3L)
171	0.93			**1987**	-	

- **1st and 3rd Longitudinal Modes Observed**

SUMMARY

- Uni-Element Hot-fire Results (LOX/GH_2)
  - Oxygen-Rich Ignition/Combustion Achieved with LOX in Uni-Element Rocket: $5 < O/F < 170$
  - Observed Flameholding at LOX Post
  - LOX Region Visualized in Flame at $O/F = 5.7$
  - Oxygen-Rich: C*-Efficiency > 92%
  - Near-Stoich.: C*-Efficiency > 96%
  - Chamber Heat Flux Characterized at $P_c = 300$ psia (800 psi Tests in Progress)
  - Smooth Combustion in Uni-Element Rocket, Fluctuations ~ 1% of P_c for 300 psia tests

Computational Fluid Dynamic Analyses of of Oxygen-Rich Preburners Utilizing Secondary Dilution

Jeffrey M. Grenda and Charles L. Merkle

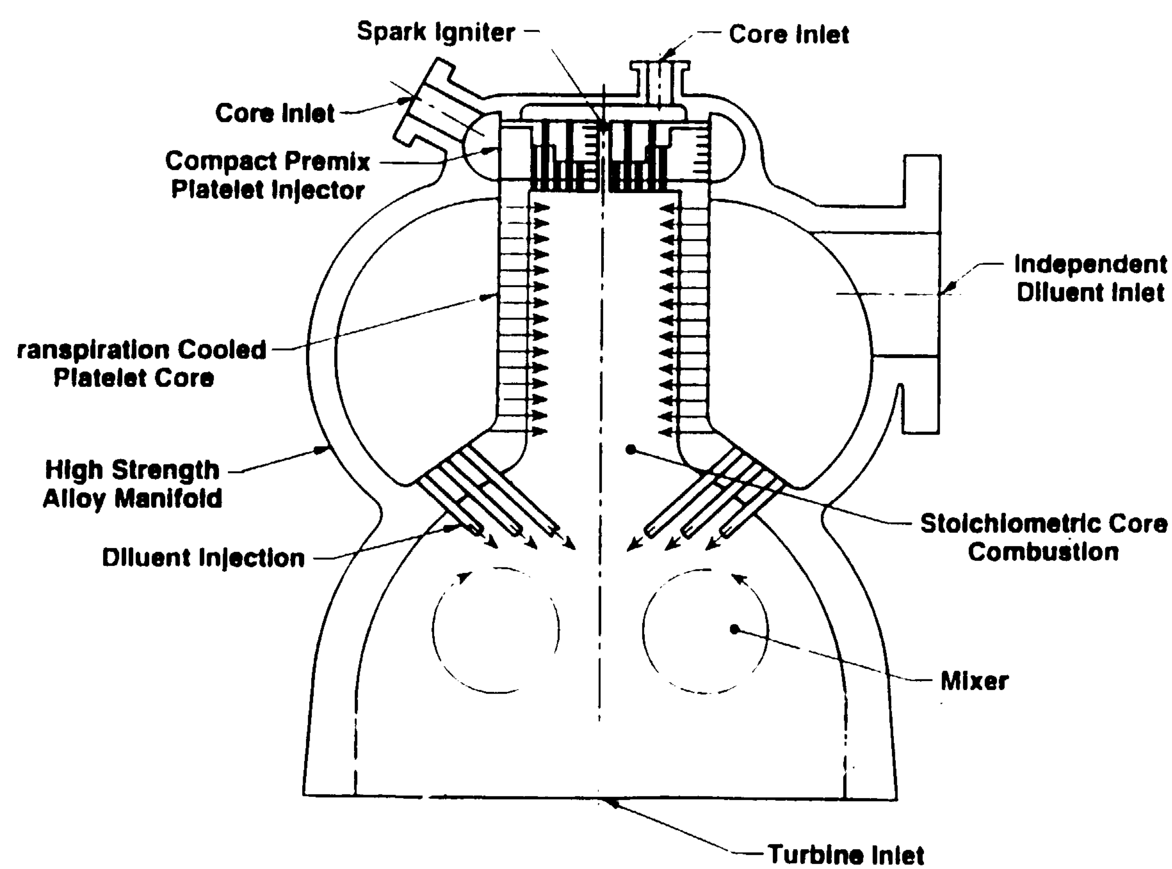
Propulsion Engineering Research Center
Department of Mechanical Engineering
The Pennsylvania State University

POTENTIAL FULL-FLOW PREBURNER DESIGNS

- Direct Injection
  - Fuel Burned with Full Oxidizer Flow Rate
  - High O/F Combustion
- Downstream Dilution
  - Fuel Burned at Near-Stoichiometric Conditions
  - Remaining Oxidizer Injected Downstream
- Design Issues:
  - Geometry and Method of Downstream Dilution
  - Mixing and Uniformity of Exit Flow
  - Ensure Vaporization of All Liquid
  - Effects of Operating Conditions

PRE-BURNER SCHEMATIC

- Near Stoichiometric Combustion Produces High Temperatures
- Diluted By Injection of Liquid Oxidizer Downstream



RESEARCH GOALS

- Use CFD as Preliminary Design Tool
  - Screen Various Geometrical Configurations
  - Identify Appropriate Parameter Ranges
  - Define Subscale Experiments
    - Geometrical Configuration
    - Parameter Ranges

- Validation of CFD Procedure
  - Compare Vaporization Predictions with Measurements
  - Assess Reliability of CFD Predictions

- Predict Full-Scale Performance
  - Address Experimental Scale-Up Issues
  - Project Pros and Cons of Various Configurations
  - Identify Important Design Parameters
  - Define Appropriate Operating Regimes

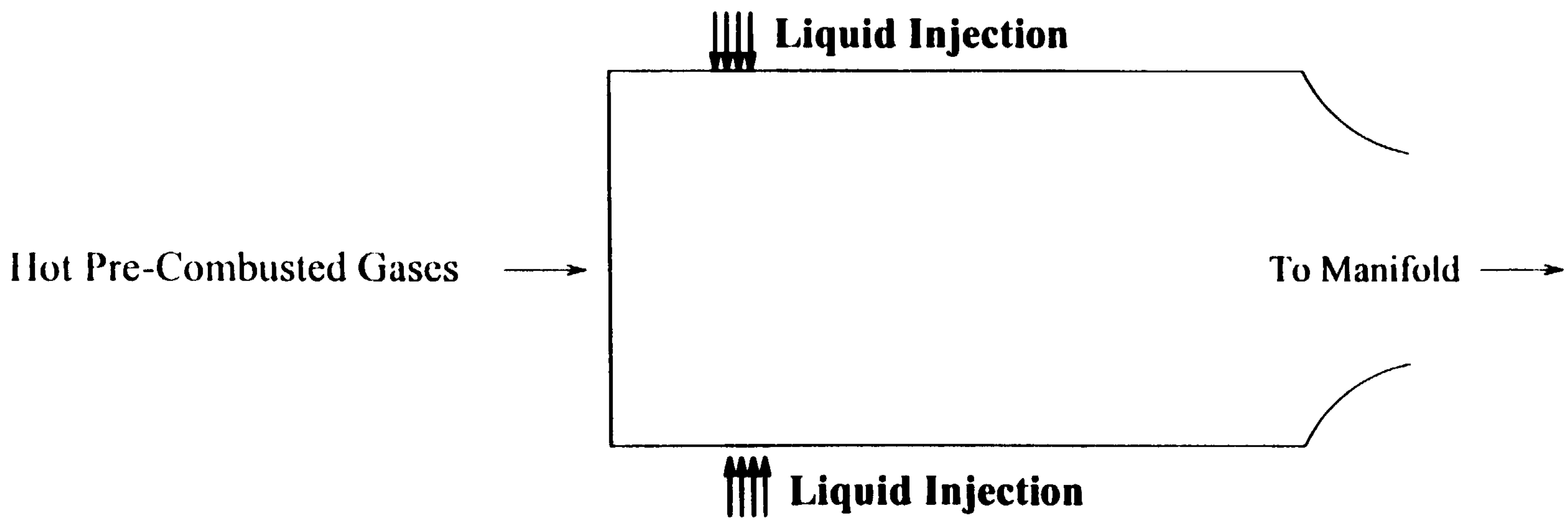
PRESENT STATUS

- Configurations Considered:
  - Axial Injection From Faceplate
  - Radial Injection From Outer Wall
  - Recessed Stoichiometric Core/Chamber

- Operating Conditions Tested:
  - O/F Ratio Variations
  - Liquid Injection Characteristics
  - Gas Phase Composition and Character
  - Chamber Length/Radius

BASIC PRE-BURNER GEOMETRIES

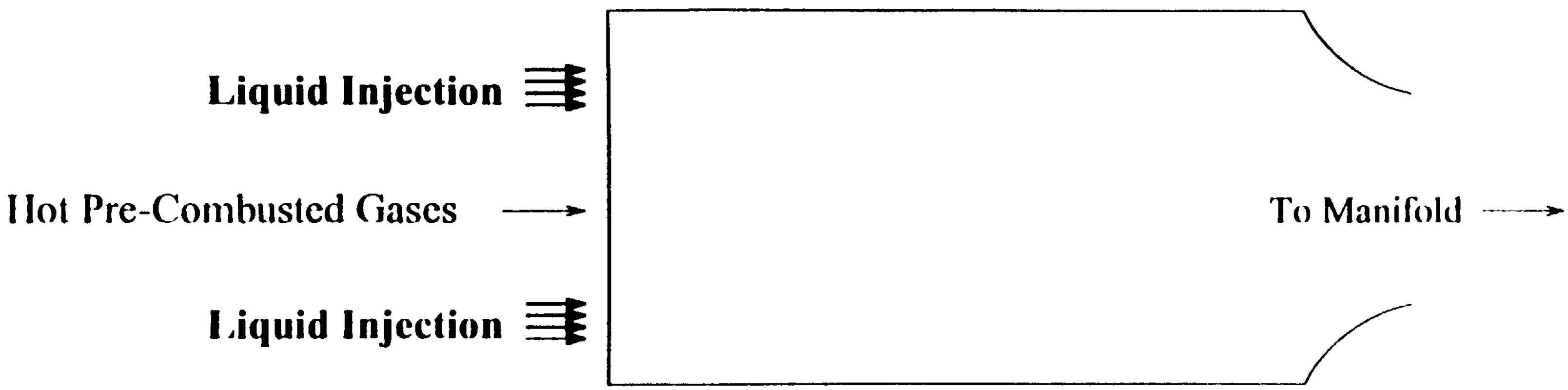
- **Radial Injection From Outer Wall:**



- **Liquid Injected Inward From Wall Injectors**
  - **Liquid Injected Either Perpendicular or Canted**
  - **Initial Drop Sizes and Velocities Stochastic**

BASIC PRE-BURNER GEOMETRIES

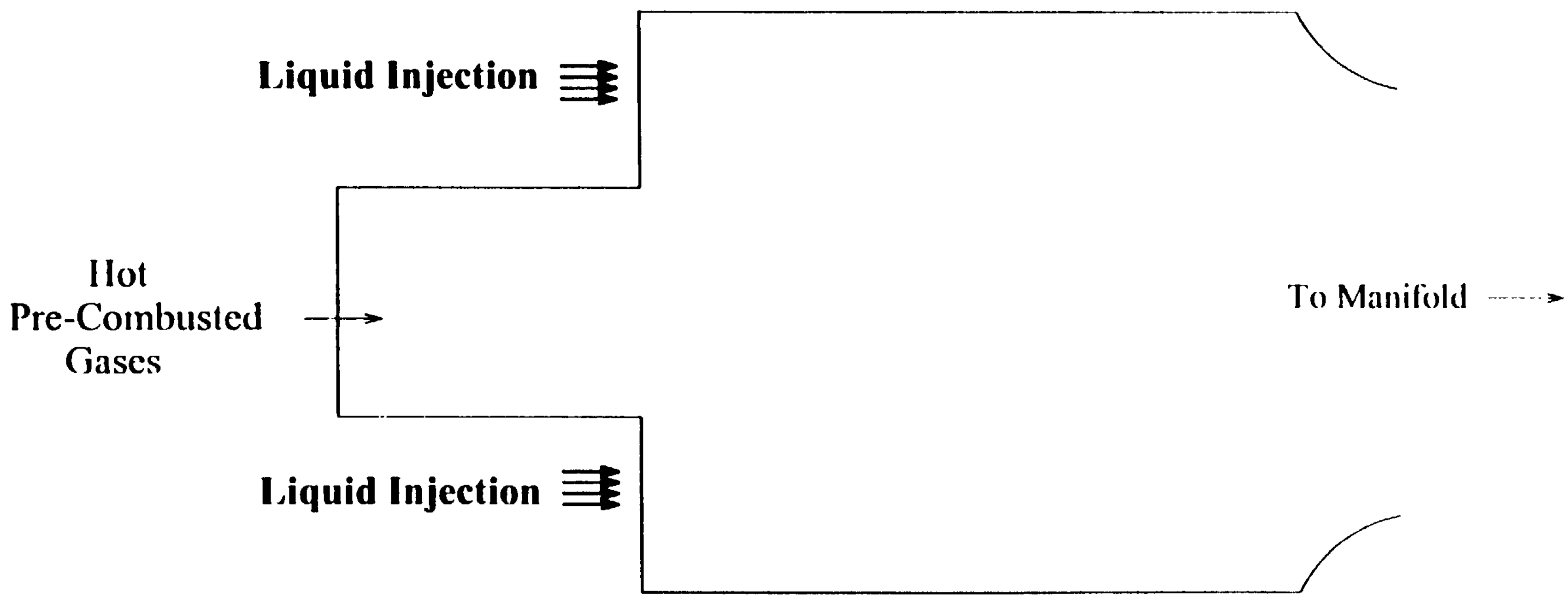
- **Axial Injection Geometry:**



- **Liquid Injected Axially From Injector Faceplate**
  - Atomization is Treated Empirically (Mean Drop Size)
  - Initial Drop Sizes and Velocities Stochastic

BASIC PRE-BURNER GEOMETRIES

- Axial Injection Including Detailed Core Region:



- Main Chamber Forms an Equivalent Backstep
  - Liquid Injected Either Axially or Canted
  - Initial Drop Sizes and Velocities Stochastic

GAS PHASE MODELING

- Gas Phase Treated in Eulerian Fashion
  - Preconditioned Navier-Stokes Equations/Species Transport
  - k-e Turbulence Modeling

$$\Gamma \frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{1}{r} \frac{\partial Fr}{\partial y} = H_{gas} + H_{liq} + L(Q_v)$$

- Requires Liquid Phase Coupling Source Terms
- Solved Implicitly for Robustness (ADI or LGS Algorithm)
- Gas Phase Solution Procedure Well-Validated Against Experimental and Analytical Solutions

DESCRIPTION OF LIQUID PHASE PROCESSES

- Injection
  - Distributed Over Finite Region
  - "Axisymmetric" Injector; 3-D Drop Velocities
  - Injector "Cone" Angle Specified

- Atomization
  - Specify Droplet Size
    - Mean: Experimental Observations; Δp
    - Distribution: Upper Limit
  - Specify Droplet Velocity
    - Mean: Determined by Injector Δp
    - Distribution: Random Function--Experimental Observation

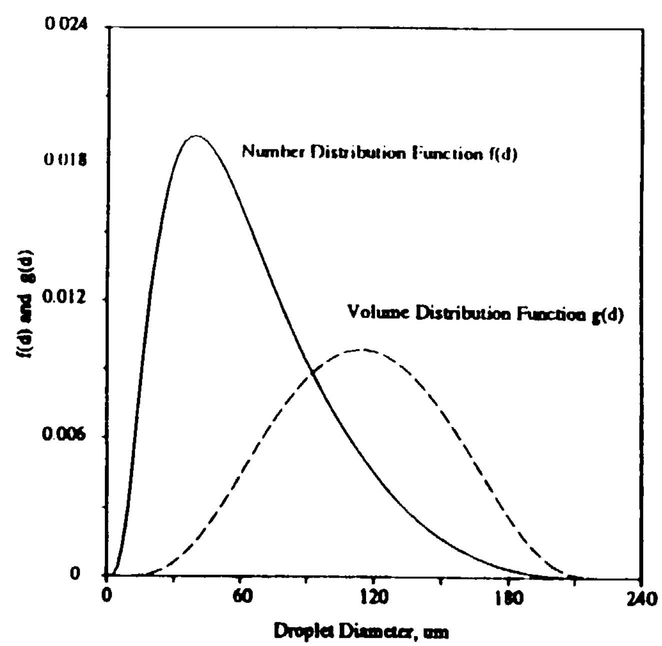
      Typical: $u = \overline{u} \pm 10\% \overline{u}$

      $v = \pm 10\% \overline{u}$

      $w = \pm 10\% \overline{u}$

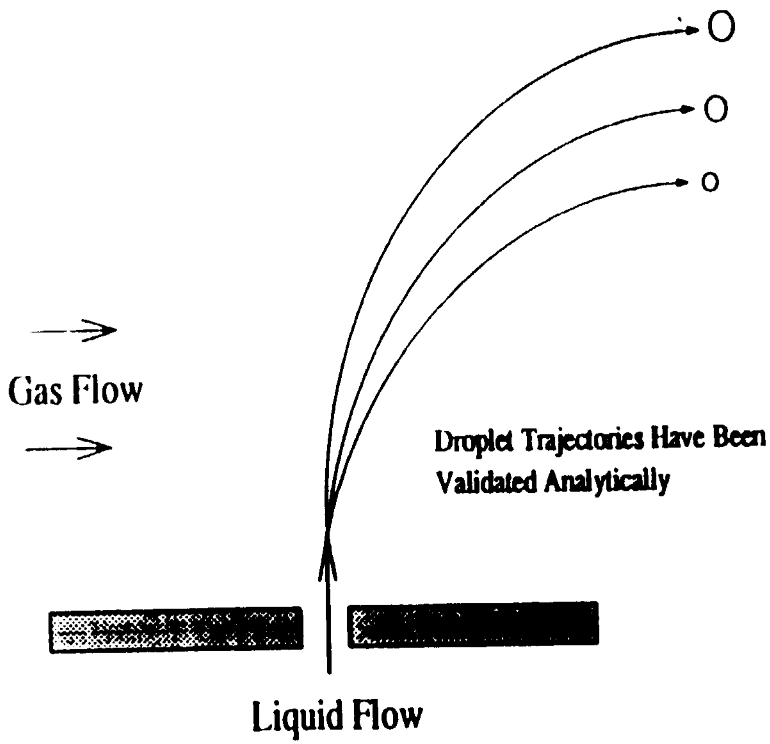
DROPLET DISTRIBUTION FUNCTIONS:

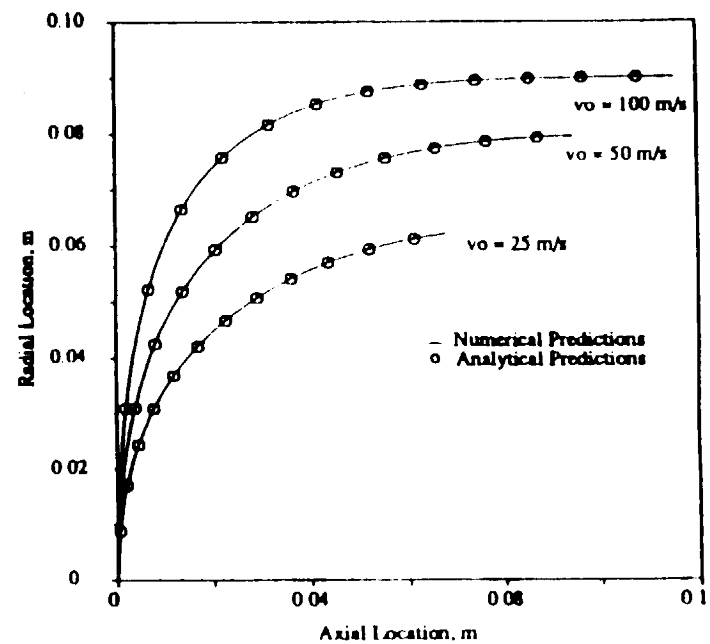
- Droplet Size Distribution is Represented by Several Models:
  - Upper-Limit Distribution Function
  - Experimental Measurements
- Number Distribution f(d) and Mass Distribution g(d)
- Liquid Partitioned into Various Droplet Sizes



LIQUID PHASE VALIDATION:

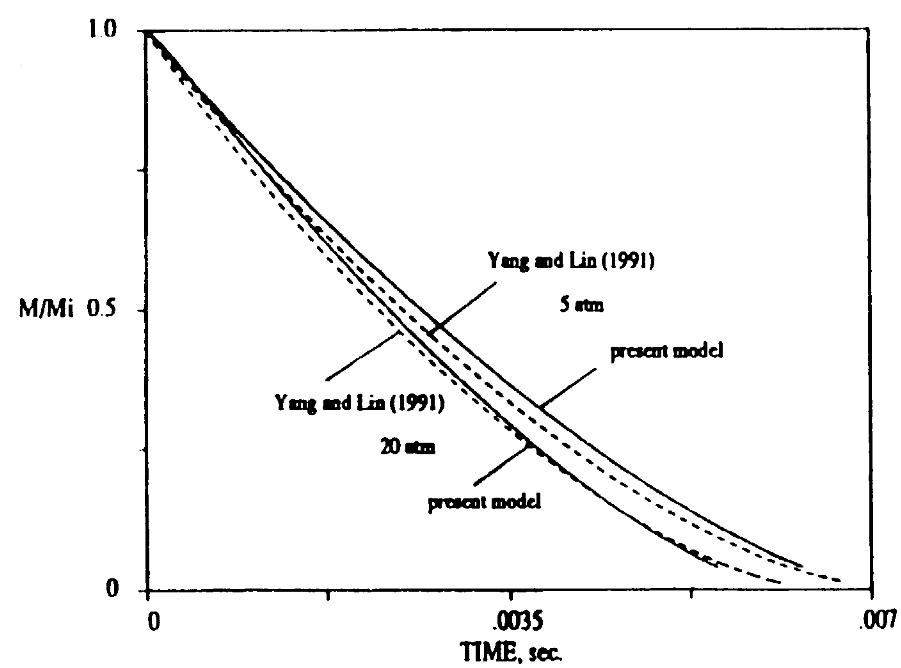
- **Trajectories Validated By Comparison With Analytical Solutions**





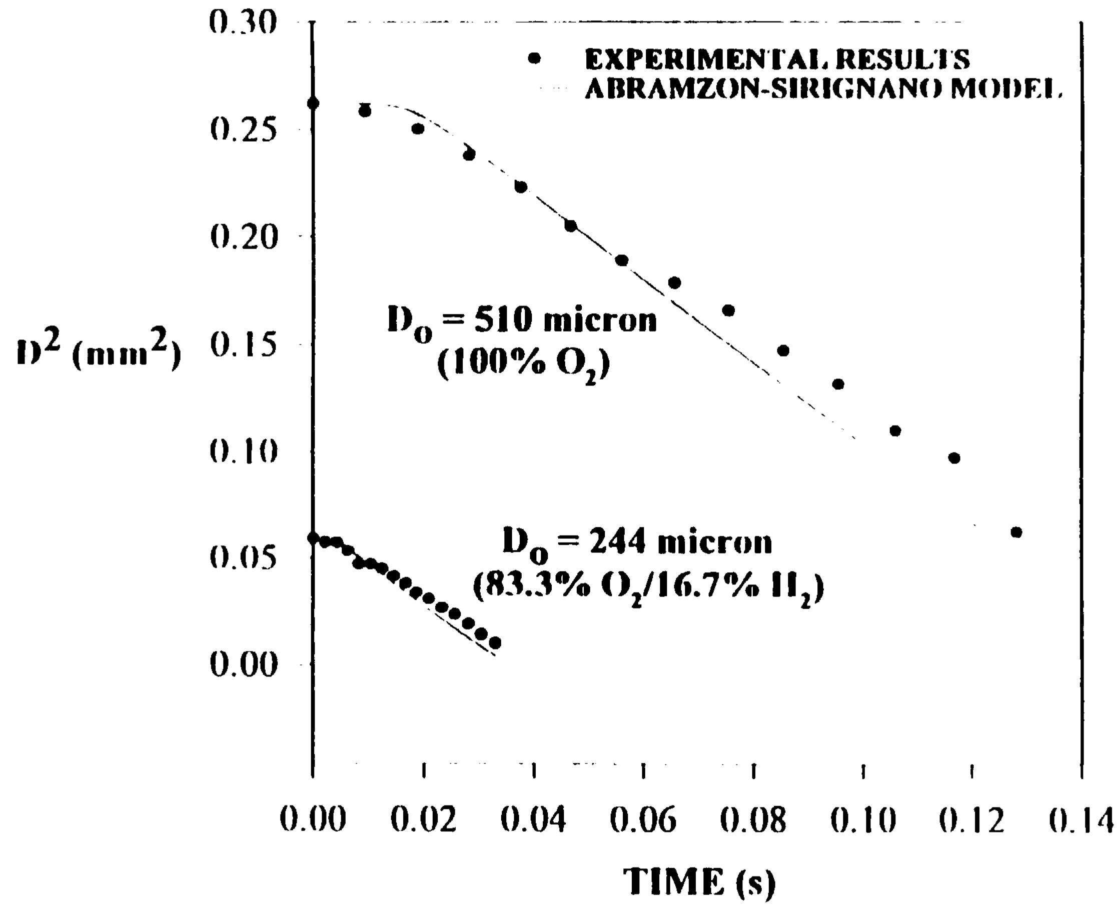
LIQUID PHASE VALIDATION:

- **Droplet Vaporization Rate Validated by Comparison With Detailed Numerical Solutions for Single Droplet**



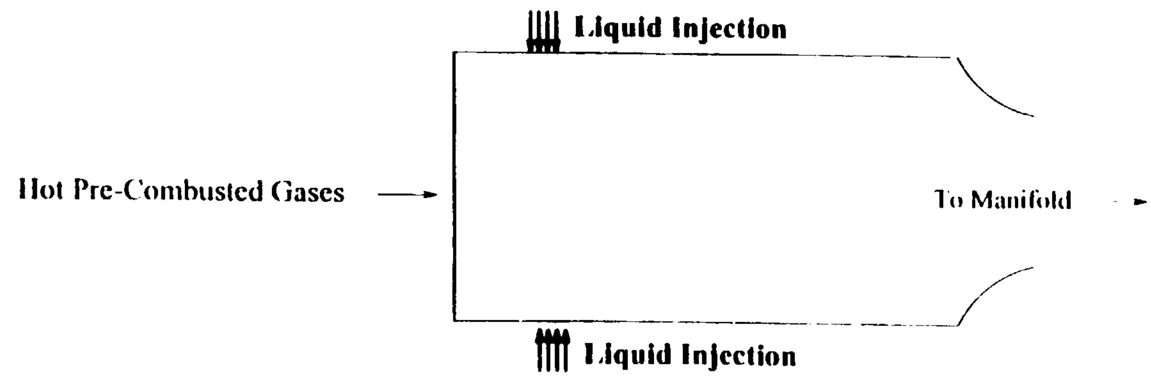
LIQUID PHASE VALIDATION:

- Droplet Vaporization Rate Compares Well With Experiments

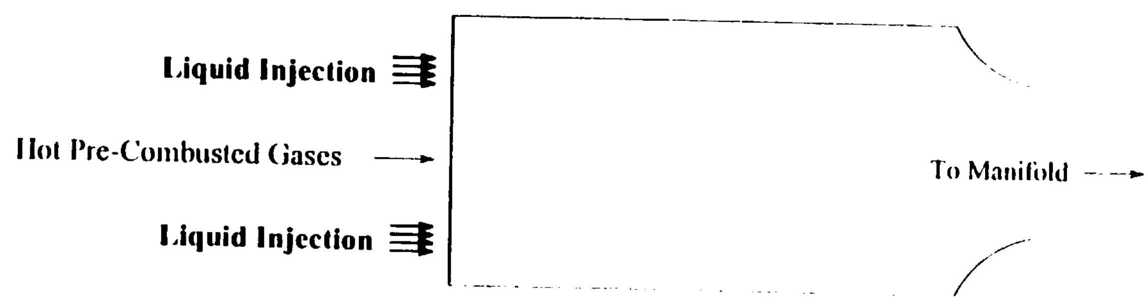


BASIC PRE-BURNER GEOMETRIES

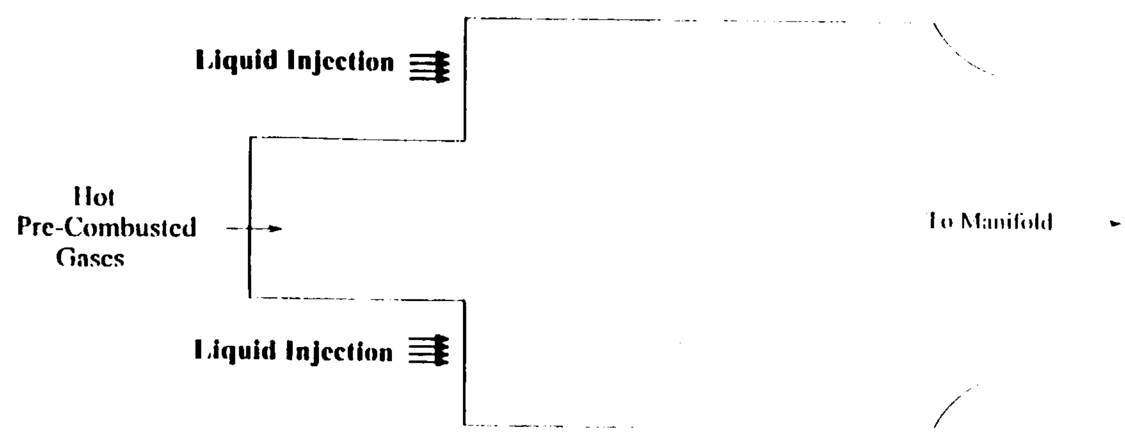
- **Radial Injection From Outer Wall:**



- **Axial Injection Geometry:**



- **Axial Injection Including Detailed Core Region:**



NOMINAL CONDITIONS:

- **Operating Conditions:**
  - Chamber Diameter of 9"
  - Injector O/F Ratio 10 (3365 K)
  - Core Mass Flow Rate 8.5 kg/sec
  - Average Gas Velocity 100 m/s

- **Design Parameters Considered:**
  - Overall Dilution O/F Ratio
  - Liquid Injection Velocity
  - Injected Droplet Diameter
  - Gas Phase Mass Flow Rate/Velocity
  - Liquid Injection Spray Angle

- **PARAMETRIC RESULTS—RADIAL INJECTION**

V_{inj} \ O/F	80	150	180
80	x	x x (V_{jet} = 50)	x
100		x x (d_{32} = 100)	x
100		x x (d_{32} = 100)	x

VARIATION IN O/F RATIO:

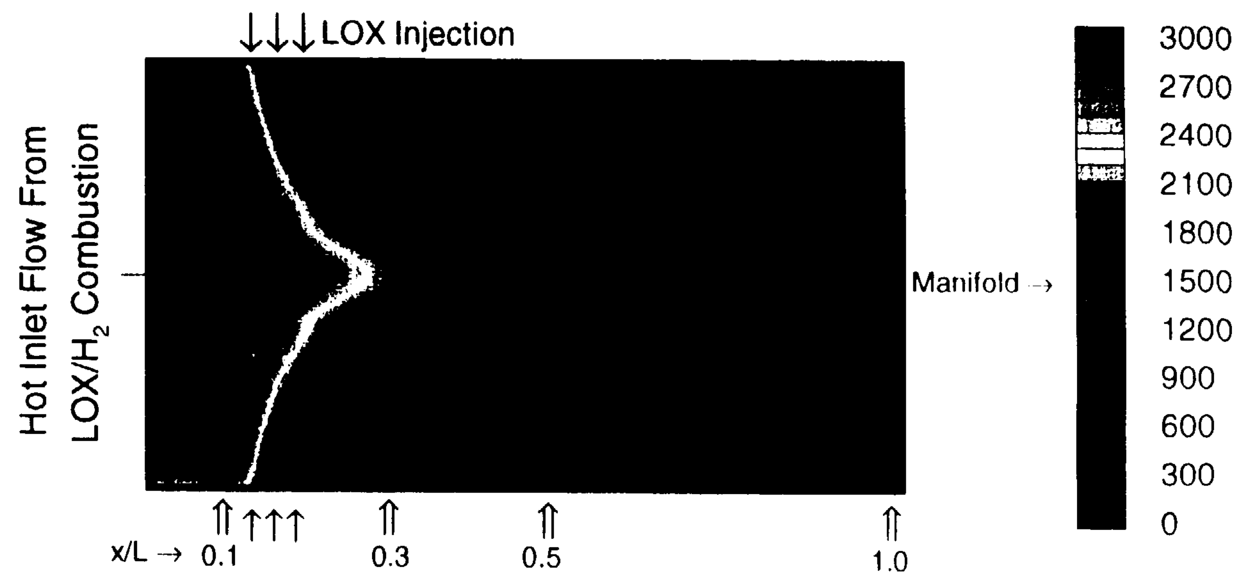
- Operating Conditions:
  - Injector O/F Ratio: 10 (3365 K)
  - Inlet Gas Velocity: 100 m/s
  - Mean Droplet Diameter: 150 um
  - Liquid Injection Velocity: 80 m/s (20% dP)

- Vary Parameter:
  - Downstream O/F: 80 to 180

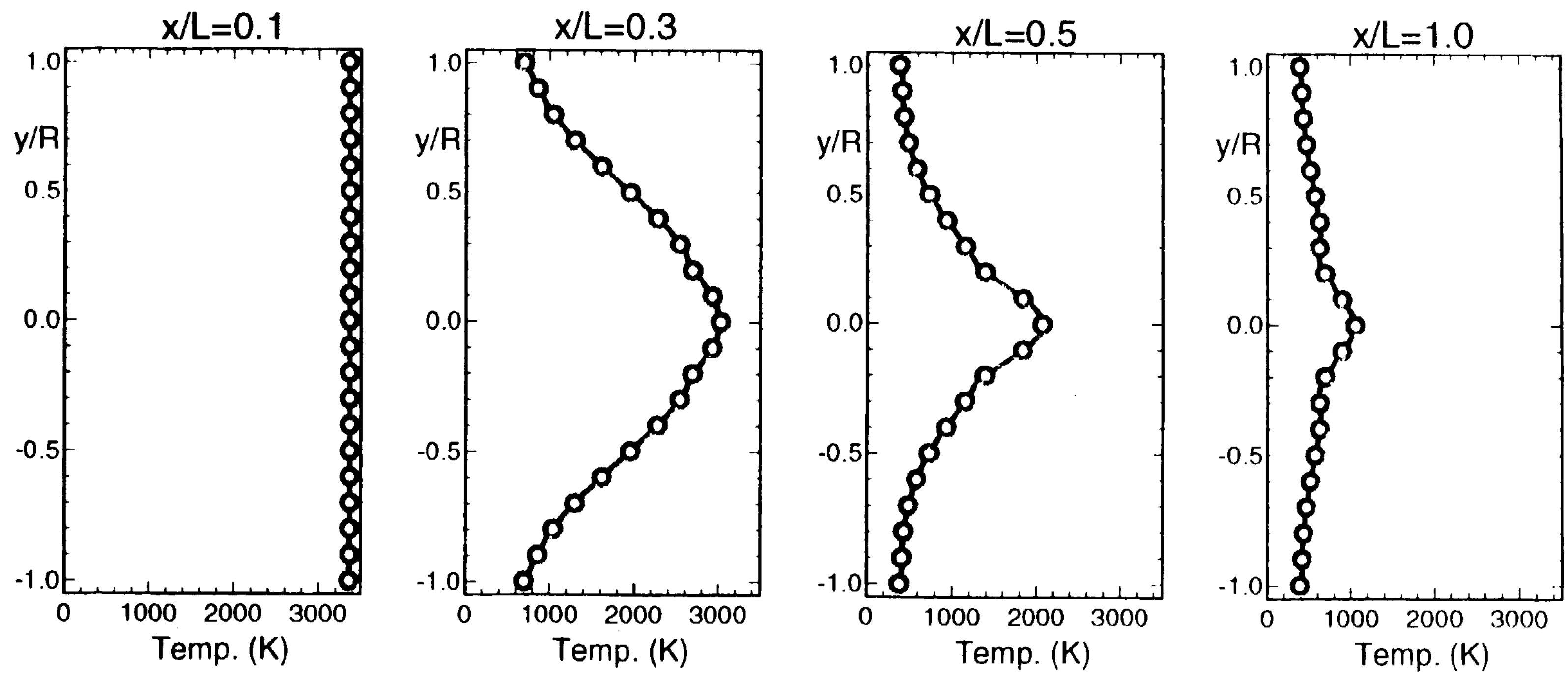
- Exit Flowfield Similar for All O/F Ratio
  - Colder Near Walls
  - Uniformity Increases With Axial Distance

Gas Temperature for LOX-Rich Preburner (Peripheral Injection Geometry)

Overall O/F = 150
V_{inj} = 80 m/s
d_{32} = 150 μm
U_{gas} = 50 m/s

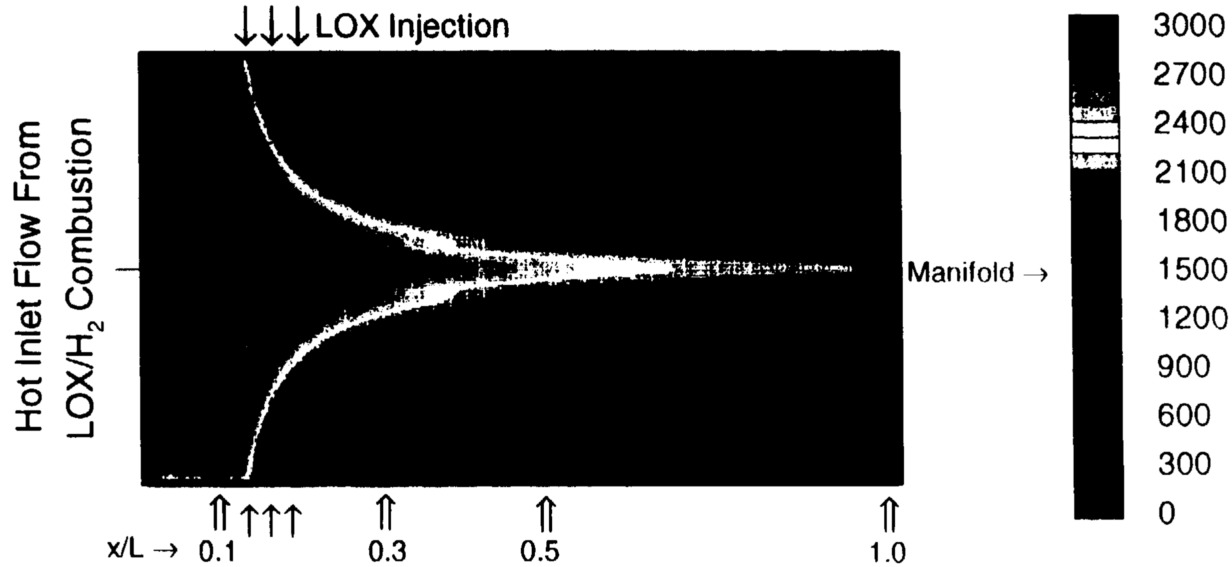


Cross-Sections of Gas Temperature

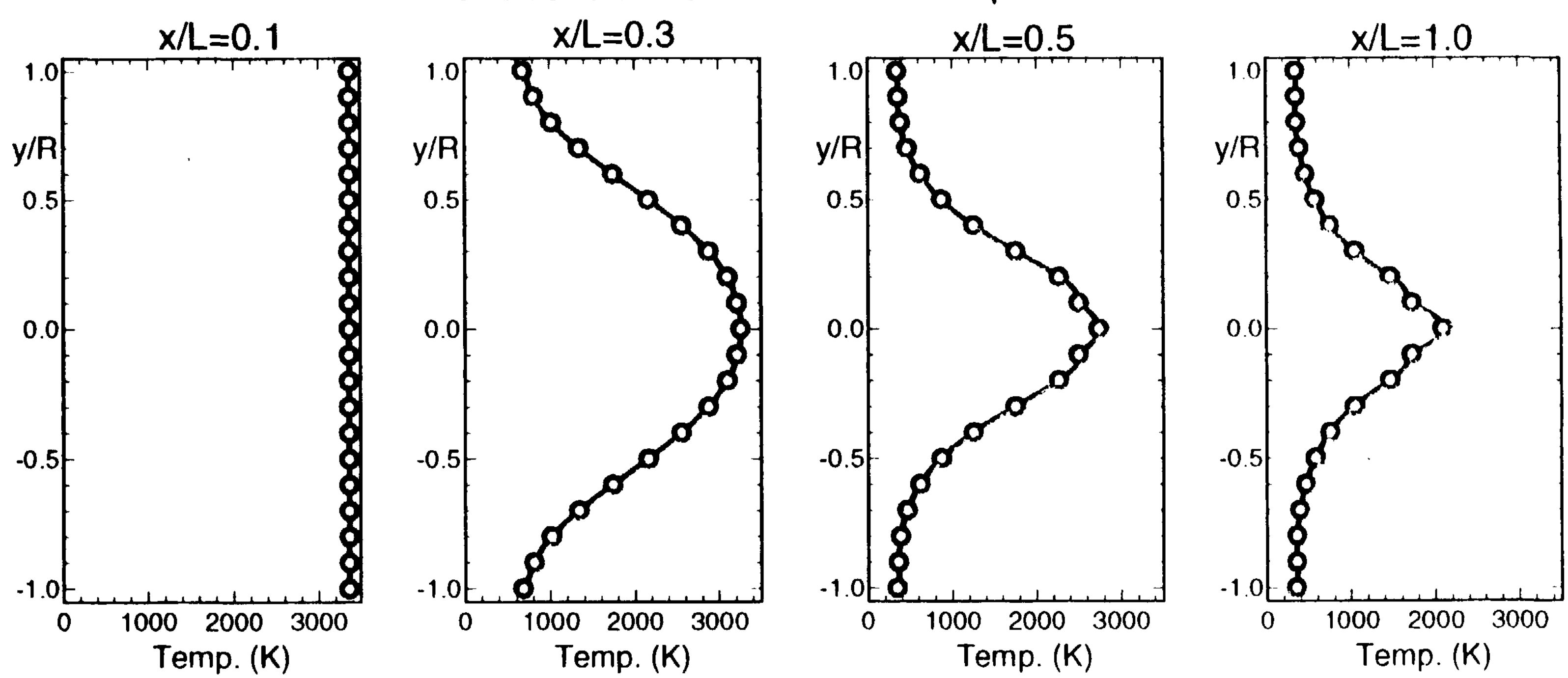


Gas Temperature for LOX-Rich Preburner (Peripheral Injection Geometry)

Overall O/F = 150
V_{inj} = 80 m/s
d_{32} = 150 μm
U_{gas} = 100 m/s



Cross-Sections of Gas Temperature

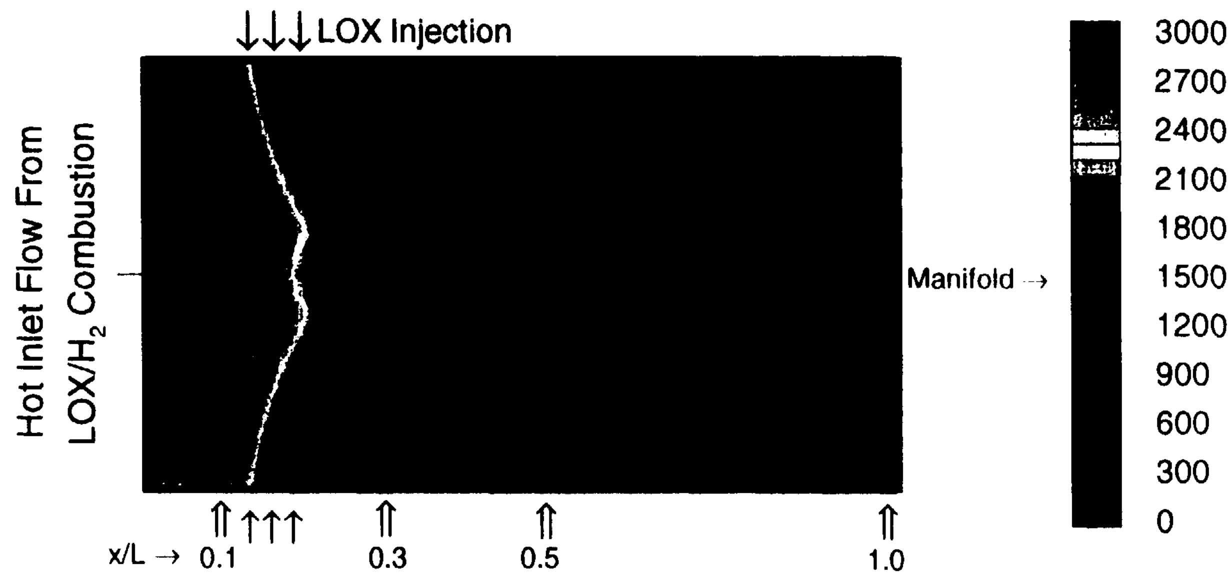


RADIAL INJECTION SUMMARY

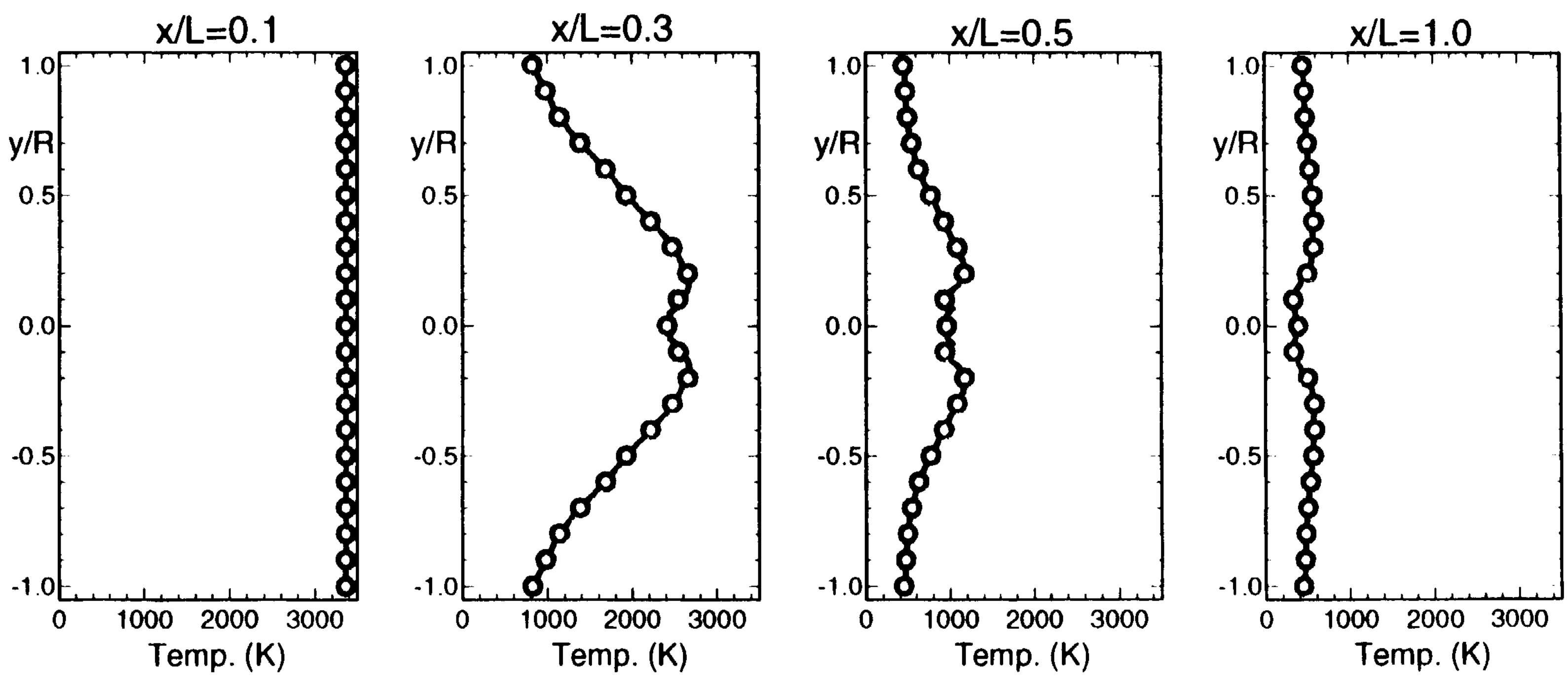
	O/F	V_{inj}	d_{32}
Best Case	180	120	150
Worst Case	150	100	100

Gas Temperature for LOX-Rich Preburner (Peripheral Injection Geometry)

Overall O/F = 180
V_{inj} = 120 m/s

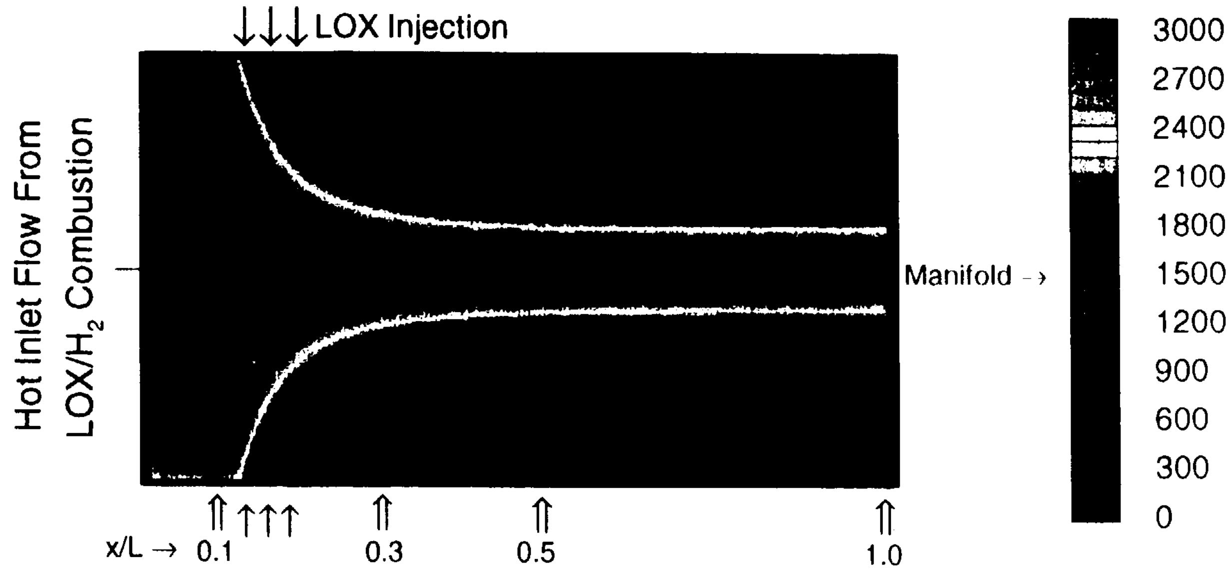


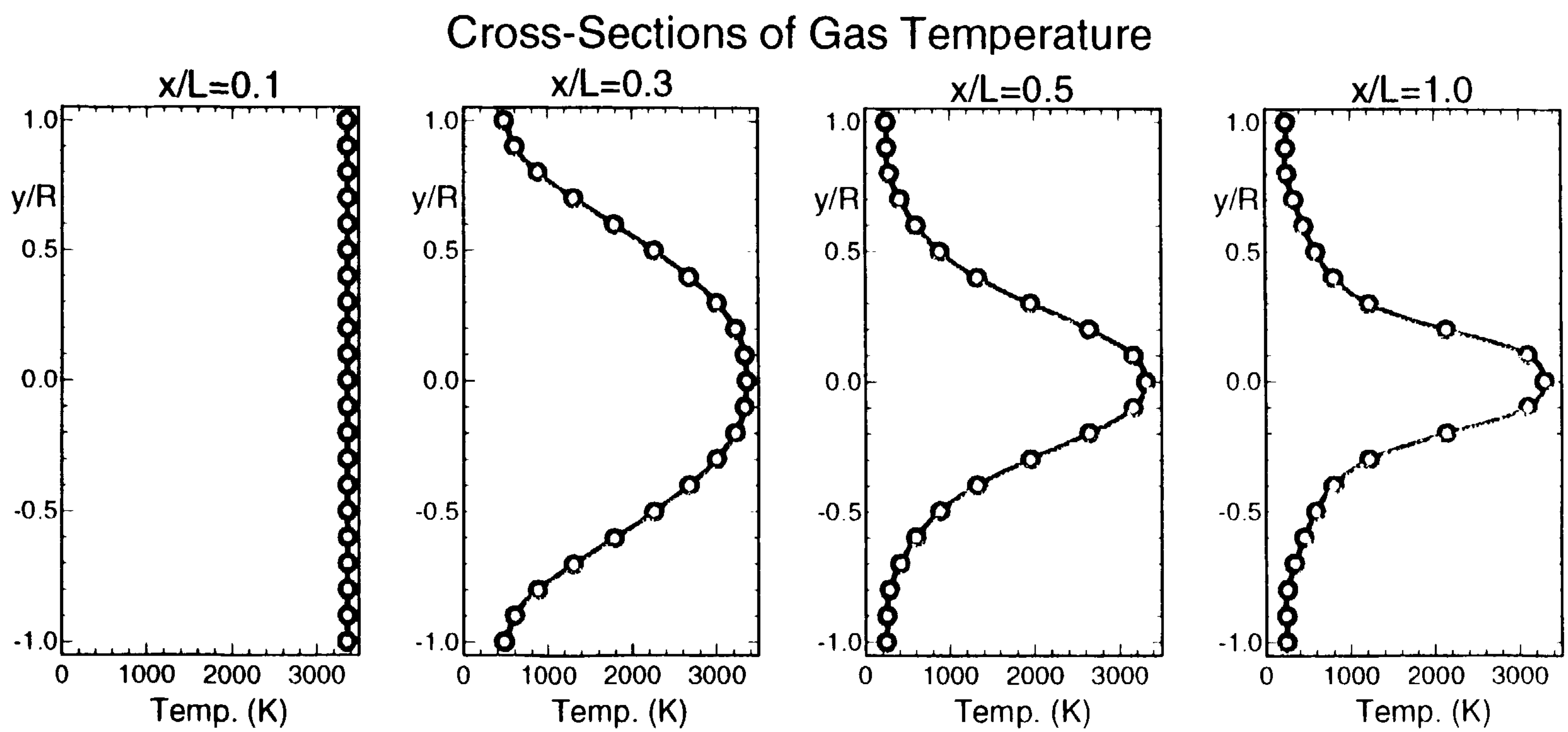
Cross-Sections of Gas Temperature



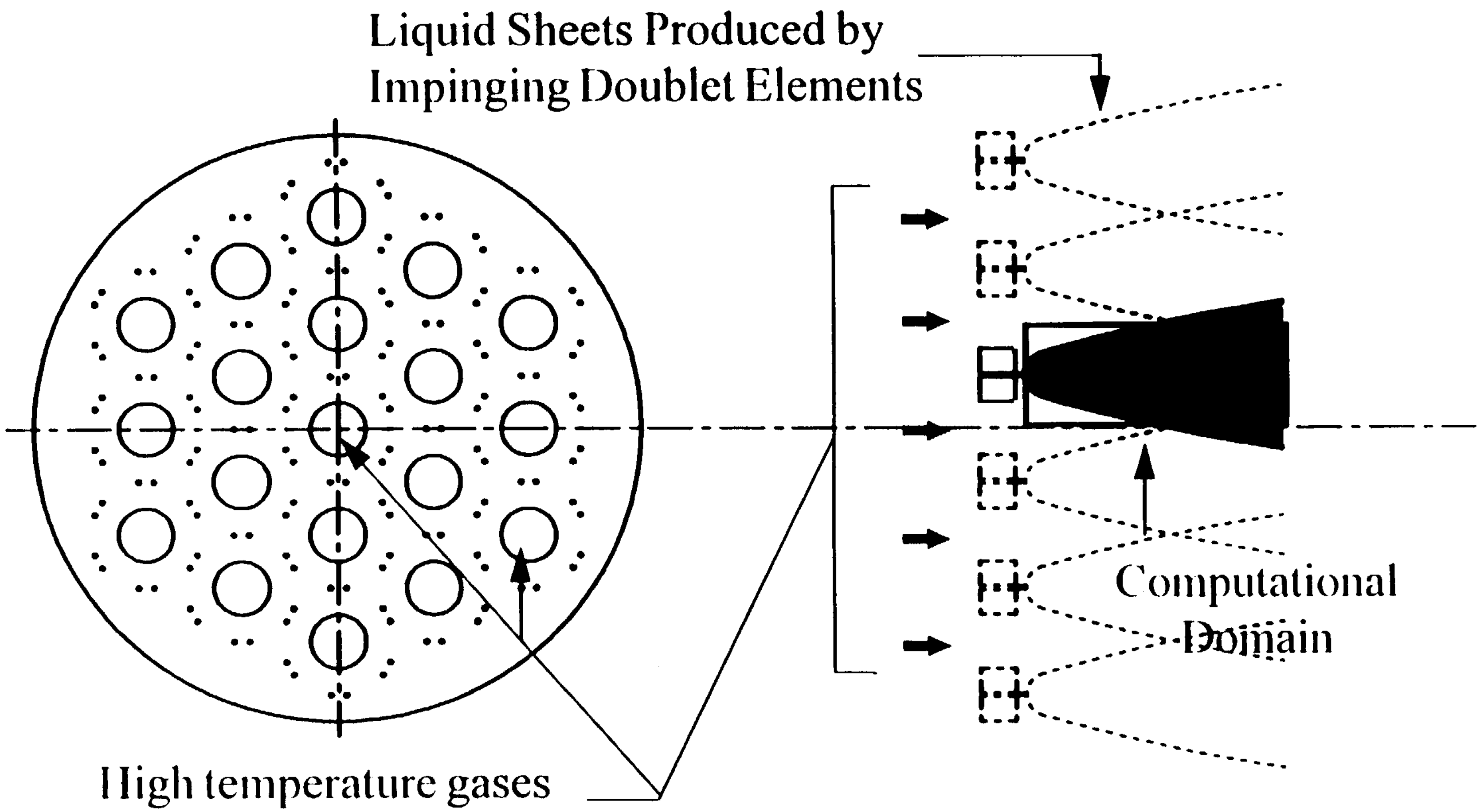
Gas Temperature for LOX-Rich Preburner (Peripheral Injection Geometry)

Overall O/F = 150
V_{inj} = 100 m/s
d_{32} = 100 μm





Schematic of Preburner Geometry



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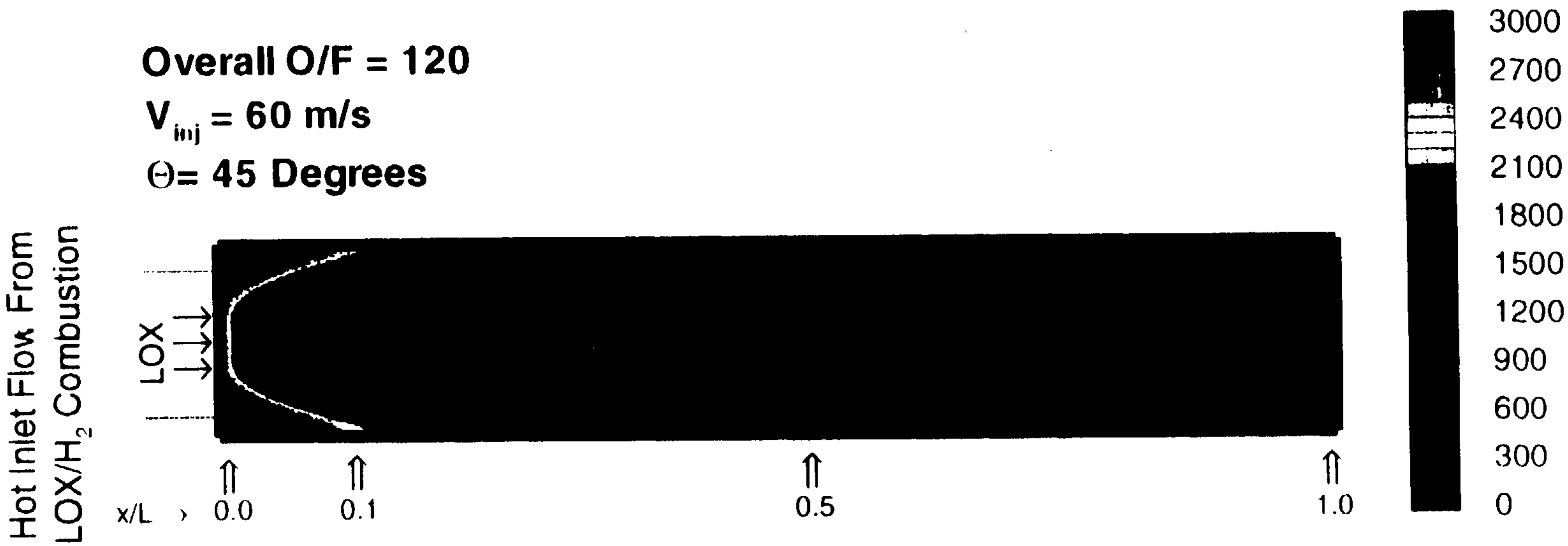
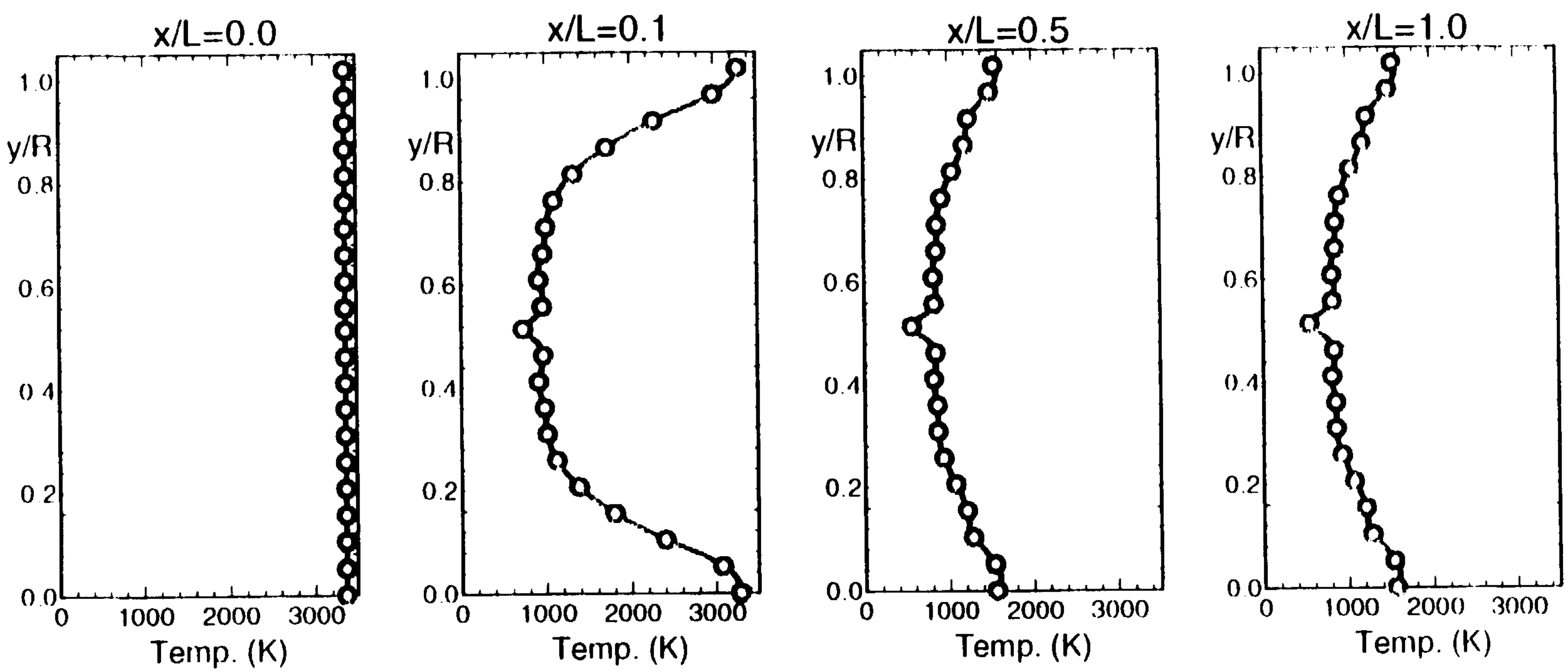
AXIAL INJECTION SUMMARY

	O/F	V_{inj}	Angle
Best Case	120	60	45
Worst Case	80	30	30

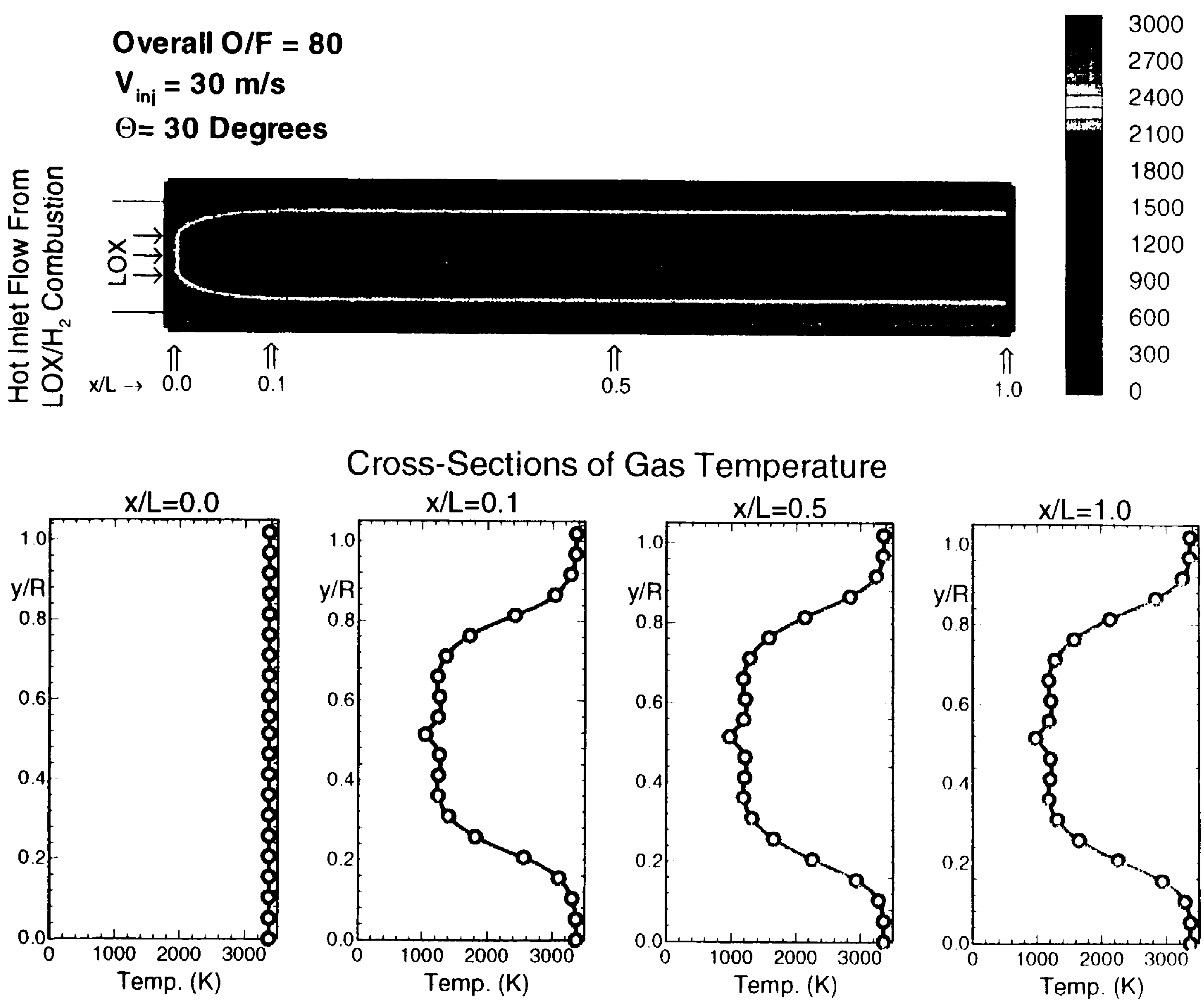
Gas Temperature for LOX-Rich Preburner (Axial Injection Geometry)

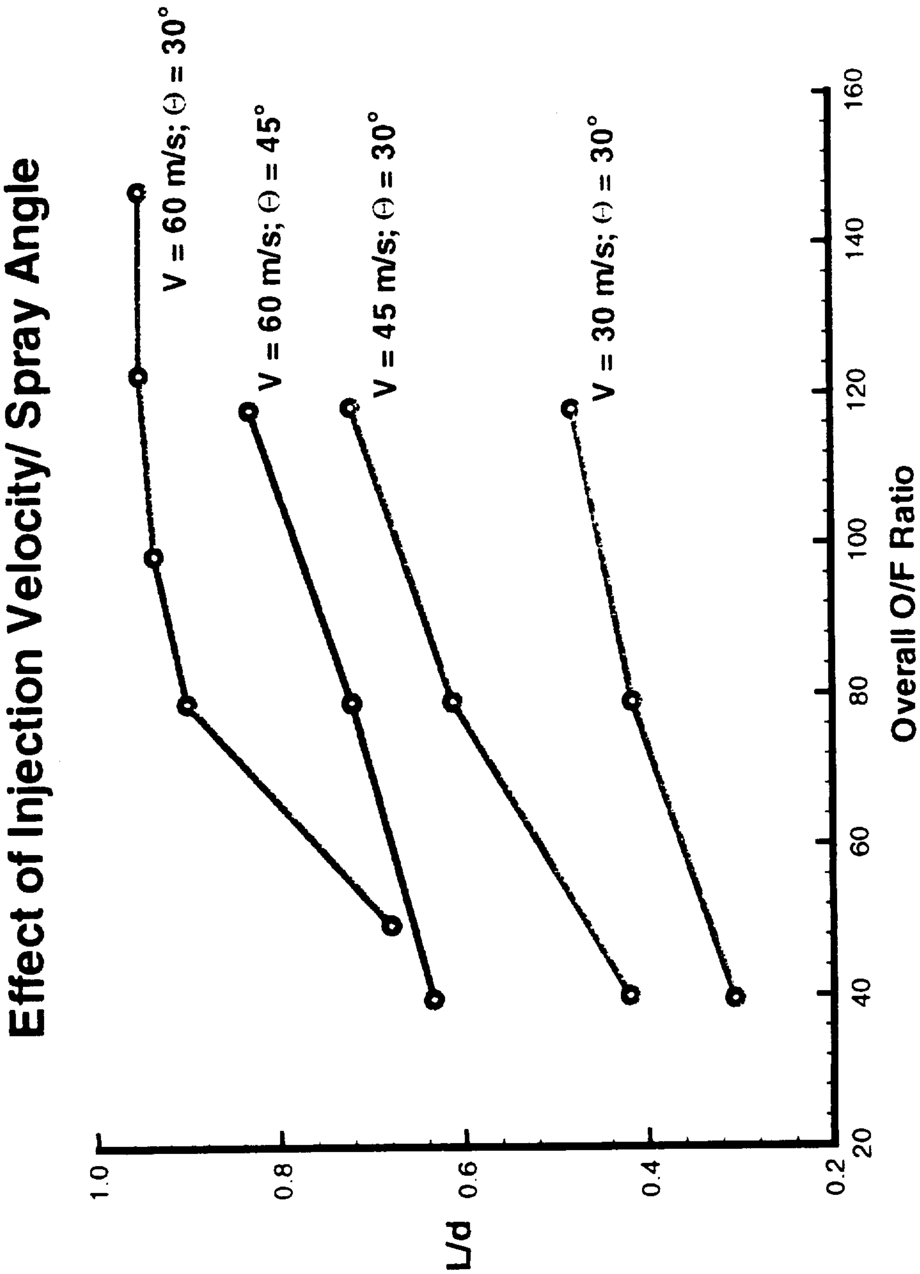


Cross-Sections of Gas Temperature



Gas Temperature for LOX-Rich Preburner (Axial Injection Geometry)





Effect of Injection Velocity/ Spray Angle
L/d
1.0
0.8
0.6
0.4
0.2
20
40
60
80
100
120
140
160
Overall O/F Ratio
V = 60 m/s; Θ = 30°
V = 60 m/s; Θ = 45°
V = 45 m/s; Θ = 30°
V = 30 m/s; Θ = 30°

CONCLUDING REMARKS

- Radial Injection is Most Effective
  - Requires Matching Between:
    - Injector Δp (Droplet Size/Velocity)
    - PreBurner Diameter
    - Mean Flow Velocity
  - Representative Δp's Match Expected PreBurner Sizes Well
  - Appropriate Control Available to Provide Acceptable Outflow Profiles
  - Viable Candidate for Downstream Dilution PreBurners
- Axial Face Plate Injection
  - Results in Acceptable Vaporization Lengths
  - Outflow Uniformity is Marginal

CONCLUDING REMARKS
(continued)

- Axial Face Plate Injection (continued)
  - Can Be Simulated in Unielement Injector
    - Useful Verification of Model Validation
  - Useful Unielement Test Configuration

- Recessed Stoichiometric Core
  - Backstep is an Aid in Mixing
  - Use With Single or Dual Axial Injection
  - Potentially Viable Candidate for Downstream Dilution PreBurners