

REPORT DOCUMENTATION PAGE

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TP-FY99-0099

MEMORANDUM FOR PRR (Contractor/In-House Publication)

FROM: PROI (TI) (STINFO)

18 May 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0099
Doug Talley, "Basic Research in Liquid Rocket Combustion at the Air Force Research Laboratory"

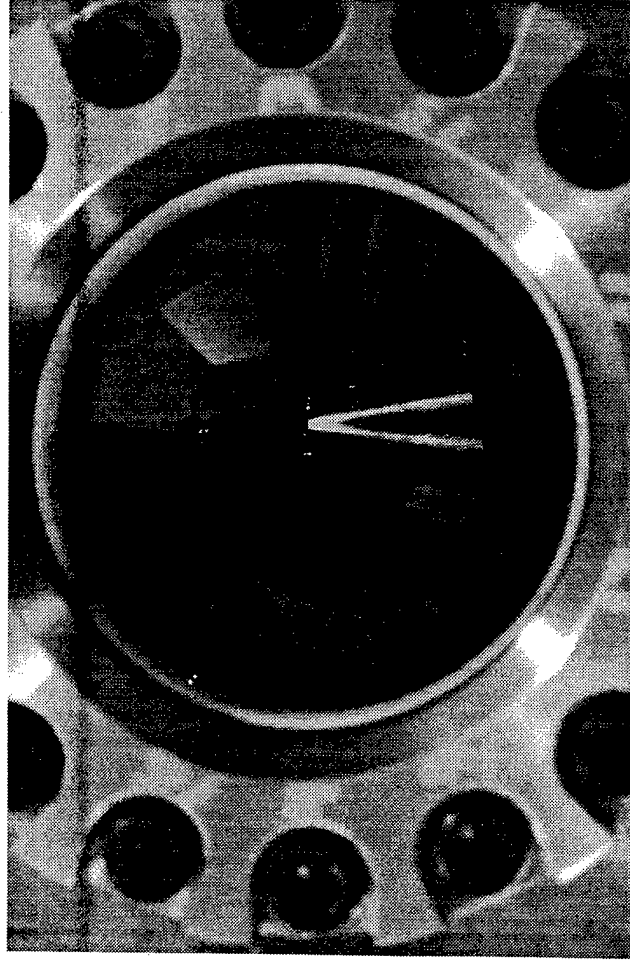
International presentation

(Statement A)

**INTERNATIONAL WORKSHOP ON
RESEARCH STATUS AND PERSPECTIVES IN
LIQUID ROCKET COMBUSTION CHAMBER FLOW DYNAMICS**



**Basic Research in Liquid Rocket
Combustion at the Air Force
Research Laboratory**



**Doug Talley
Propulsion Sciences
and Advanced
Concepts Division**

27-28 May 1999

Integrated High Payoff Rocket Propulsion Technology Program (IHPRPT) **GOALS**

Boost and Orbit Transfer Propulsion

	<u>2000</u>	<u>2005</u>	<u>2010</u>
• Reduce Stage Failure Rate	25%	50%	75%
• Improve Mass Fraction (Solids)	15%	25%	35%
• Improve ISP (sec)	14	21	26
• Reduce Hardware Costs	15%	25%	35%
• Reduce Support Costs	15%	25%	35%
• Improve Thrust to Weight (Liquids)	30%	60%	100%
• Mean Time Between Removal (Mission Life-Reusable)	20	40	100

Spacecraft Propulsion

• Improve $I_{tot}/Mass_{(wet)}$ (Electrostatic/Electromagnetic)	20%/200%	35%/500%	75%/1250%
• Improve Isp (Bipropellant/Solar Thermal)	5%/10%	10%/15%	20%/20%
• Improve Density-Isp (Monopropellant)	30%	50%	70%
• Improve Mass Fraction (Solar Thermal)	15%	25%	35%

Tactical Propulsion

• Improve Delivered Energy	3%	7%	15%
• Improve Mass Fraction (Without TVC/Throttling)	2%	5%	10%
• Improve Mass Fraction (With TVC/Throttling)	10%	20%	30%



Required Injector Characteristics

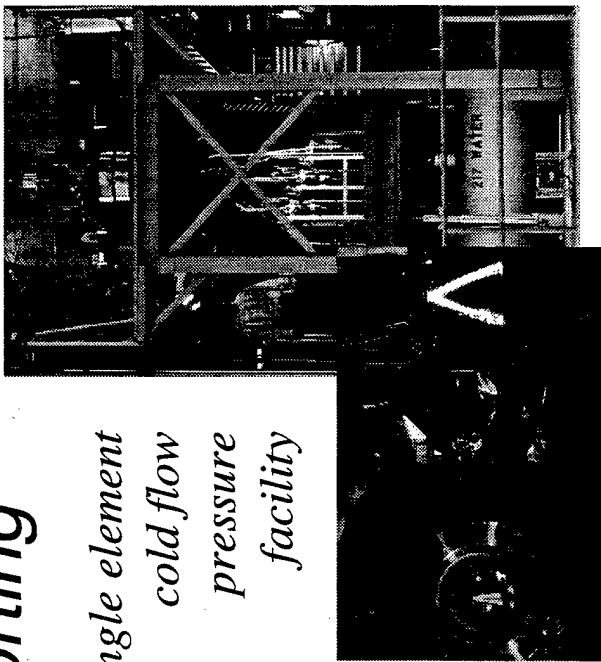
- Complete combustion in the shortest possible length
 - Main injectors: performance vs weight tradeoffs
 - Preburners/GG's: downstream component interactions, eg, turbine blades, etc
- Acoustically stable
 - Chamber modes
 - Feed system coupling
- Chamber/wall compatibility
 - Heat transfer/cooling
 - Oxygen blanching
- Minimize pressure drop
- Throttling
- Ignitable; minimum ignition transients
- Cost, weight
- The "ilities":
 - Reliability
 - Maintainability
 - Manufacturability
 - Durability
 - Operability



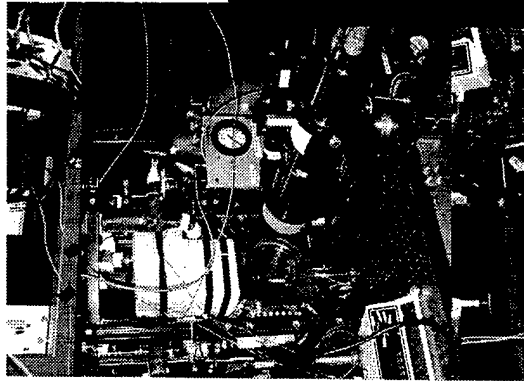
Facilities currently supporting basic research

- All facilities designed to provide optical access at pressures to 2000 psi (136 atm).

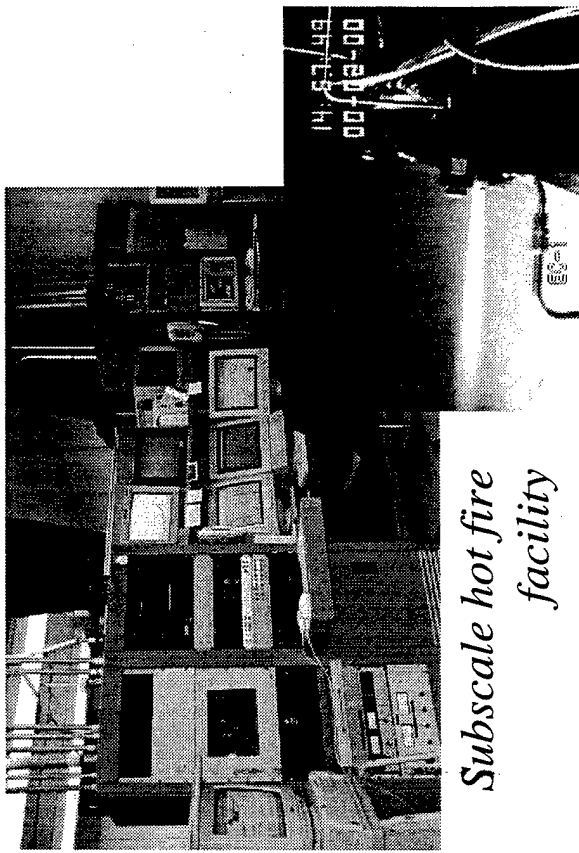
*Single element
cold flow
pressure
facility*

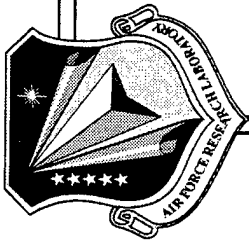


*Supercritical
pressure facility*



*Subscale hot fire
facility*





Single element cold flow pressure facility

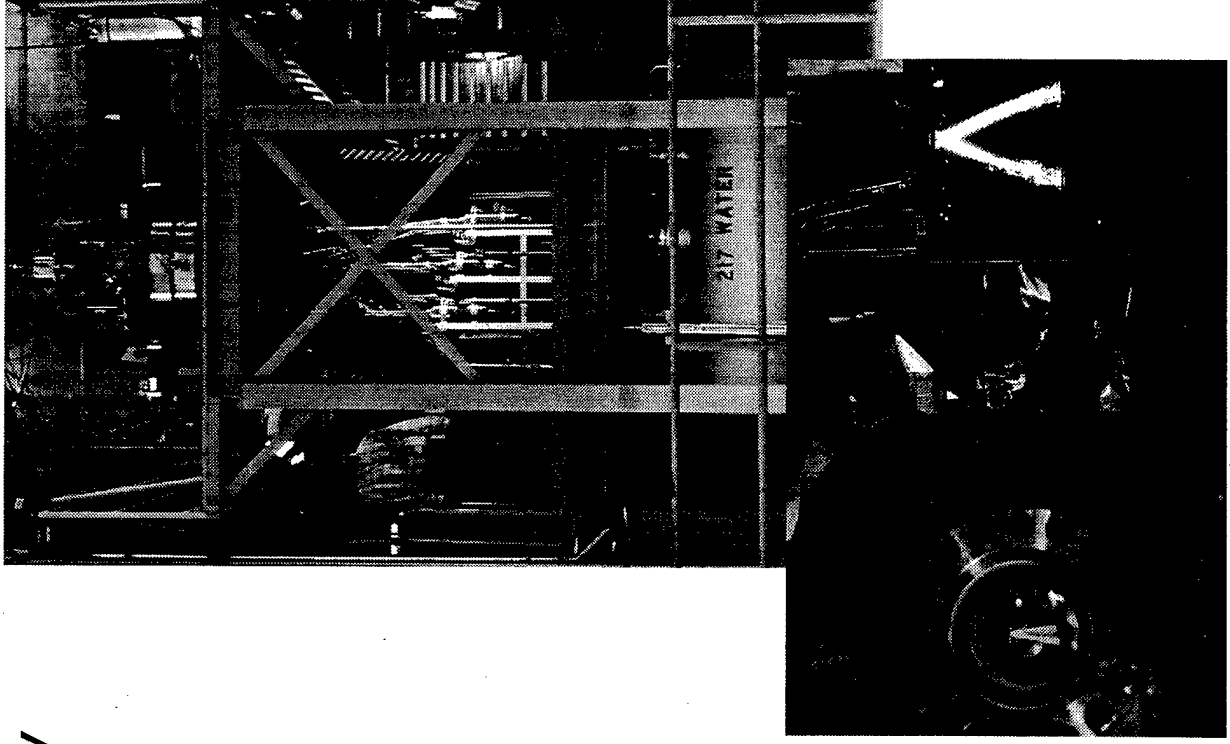
Gas simulants	N ₂ (g), He(g)
Liquid simulant	H ₂ O(l), others
Window Purge gas	N ₂ (g), He(g)
N ₂ mass flow rate	.20 lbm/s (.09 Kg/s)
He mass flow rate	.20 lbm/s (.09 Kg/s)
H ₂ O mass flow rate	4.0 lbm/s (1.8 Kg/s)
Max. test art. press.	2000 psi (136 atm)
Max. Fuel sim. press.	3000 psi. (204 atm)
Max. Ox sim. press.	3000 psi. (204 atm)

Windowed test chamber with 5.5" (14 cm) of axial injector travel and a linear translating injector stage with 5" (13 cm) total radial travel inside chamber.

Ability to simulate manifold cross velocities to 30 ft/s (9.1 m/s).

27 tube traversable mechanical patternator

Phase Doppler, Malvern, other diagnostics





Subscale hot fire facility

Fuel	H ₂ (g), CH ₄ (g)
Oxidizer	O ₂ (g)
Purge gas	N ₂ (g), He(g)
H ₂ mass flow rate	.15 lbm/s (.07 Kg/s)
CH ₄ mass flow rate	.25 lbm/s (.11 Kg/s)
O ₂ mass flow rate	1.0 lbm/s (.45 Kg/s)
N ₂ mass flow rate	.5 lbm/s (.23 Kg/s)
Water flow rate	16 lbm/s (7 Kg/s)
Max. system press.	2640 psi. (179 atm)

128 ch, 200 kbs scanning A/D

16 ch, 2 MHz per ch A/D, independently controlled

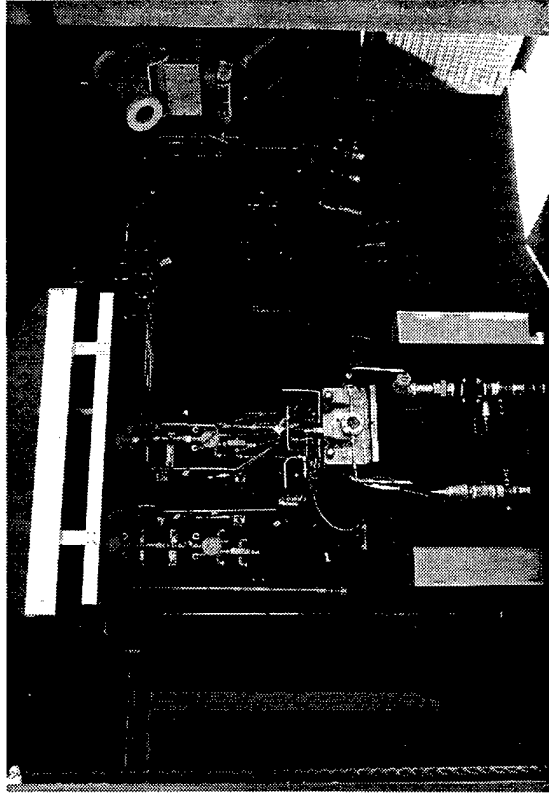
Central laser/optics room

Installing in 1999

2000 psi liquid hydrocarbon capability

2000

LOX capability





Supercritical pressure facility

Chamber

Stainless

Optical access

2 facing sapphire

13 cm dia windows

2 facing slot-shaped
quartz (12 x 1.3 cm)

Max chamb. press.

2000 psi (136 atm)

Chamb. temp.

473 K

Injected fluid

O₂, N₂, HC, and
mixtures

Ambient fluid

N₂, He, and mixtures

Injected mass flow rate

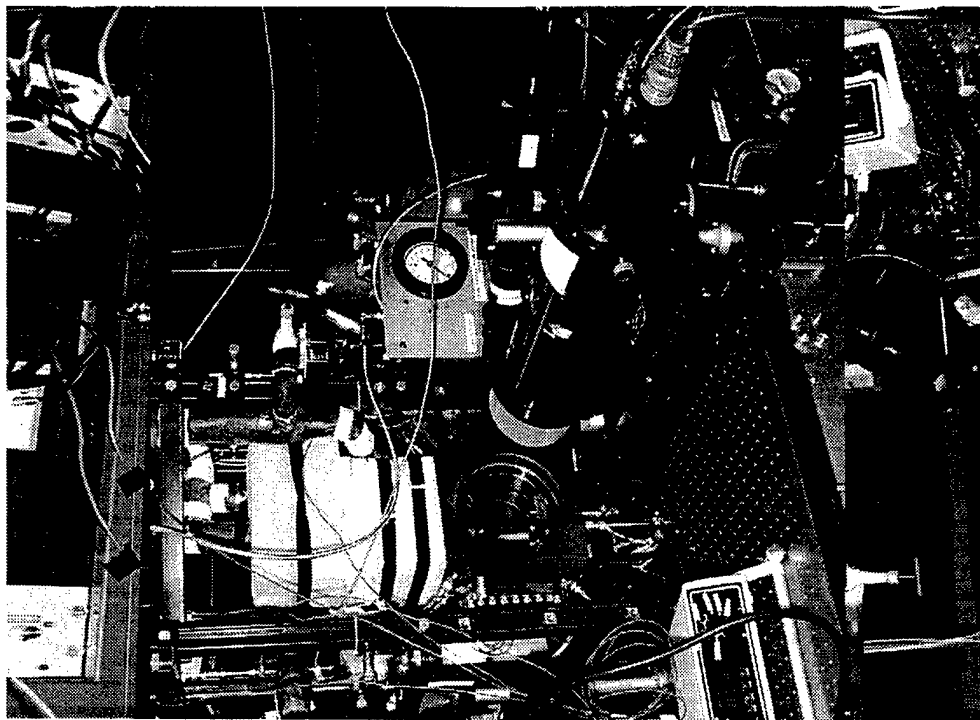
400 mg/s

Cryogenic cooler

85 K

Mass flow meters

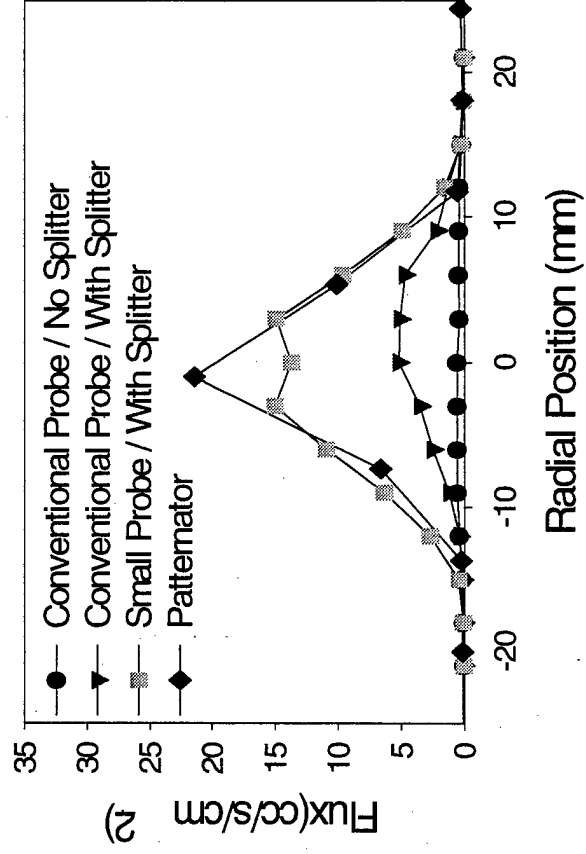
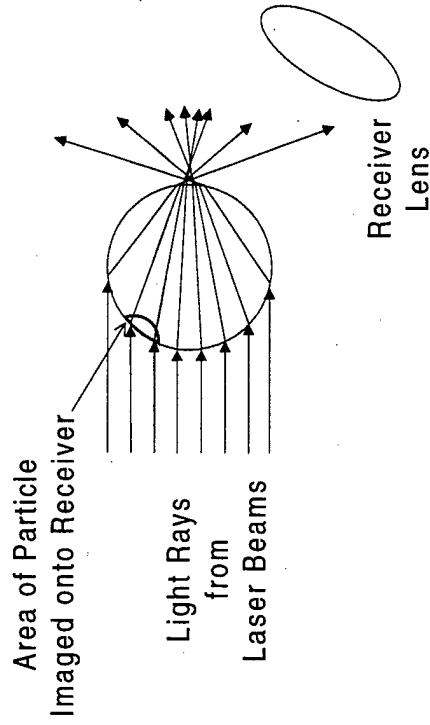
up to 10,000 SLPM

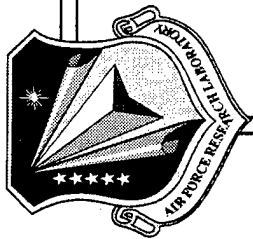




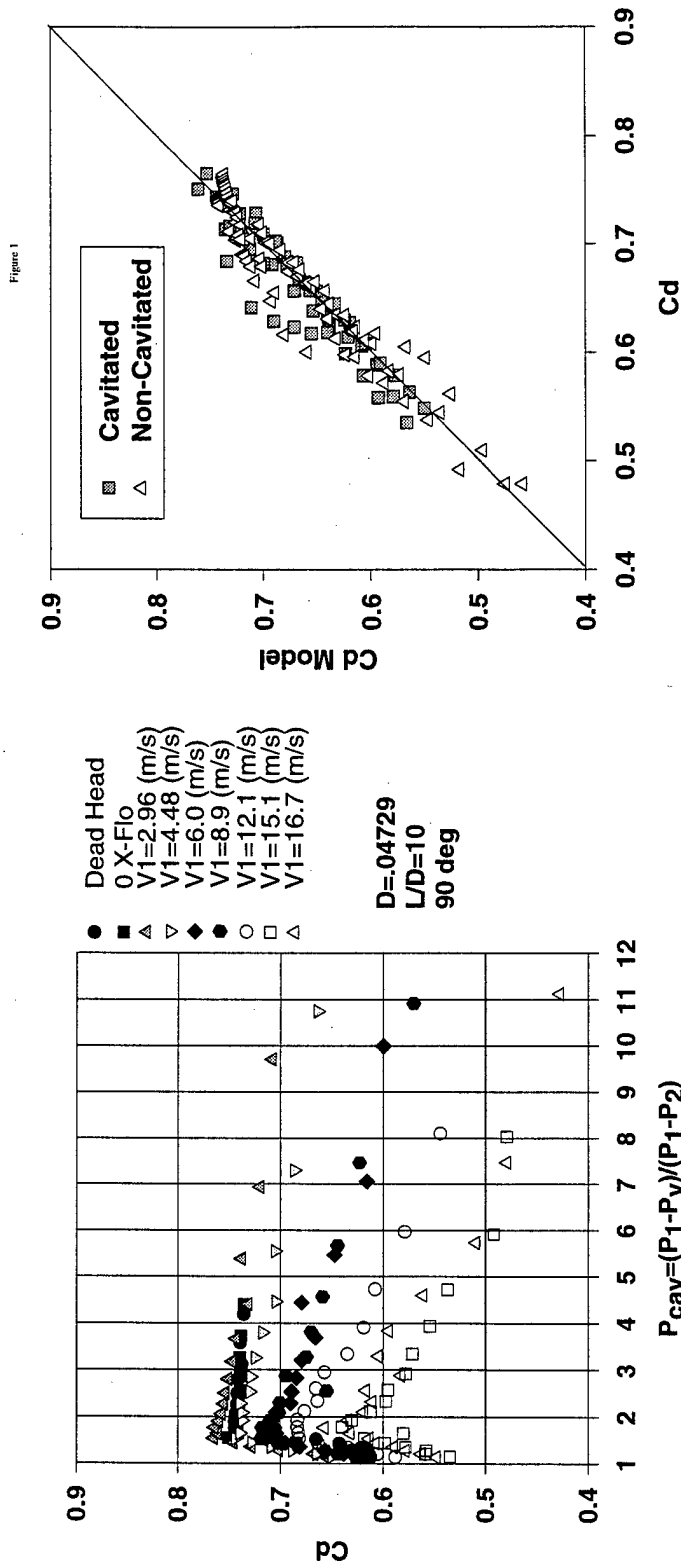
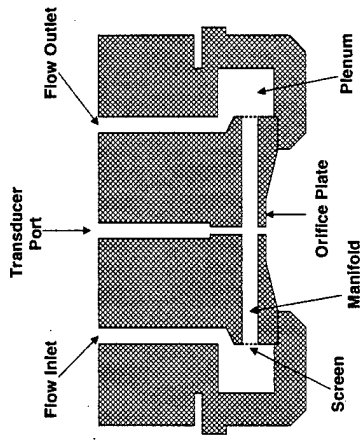
Dense Spray Diagnostics

- Goal - Extend existing diagnostic techniques into the dense spray regime where $N > 10^5 \text{ cc}^{-1}$.
- The combination of a small probe volume and a flow splitter resulted in a dramatic improvement in PDPA volume flux measurements in a dense spray.



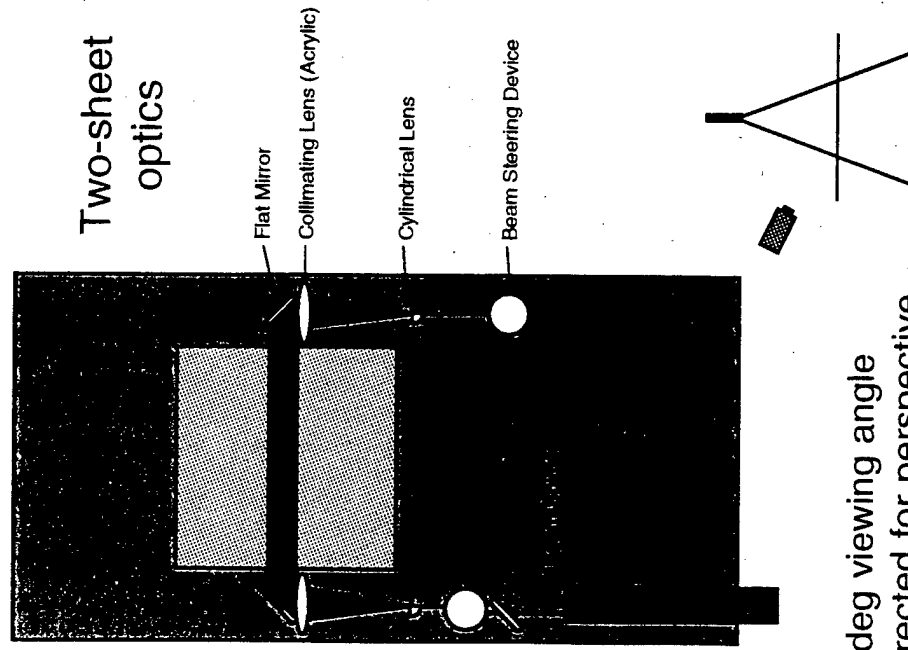


Effect of Crossflow on Orifice Discharge Coefficients



D=1.19 mm, L/D=10, $P_1=69$ MPa

TWO SHEET CORRECTION FOR LASER EXTINCTION



Camera response*

$$G = KI\rho$$

Along a ray,

$$\frac{dG_l}{G_l} = \frac{dl_l}{I_l} + \frac{d\rho}{\rho}$$

$$\frac{dG_r}{G_r} = \frac{dl_r}{I_r} + \frac{d\rho}{\rho}$$

Beer's law scattering is the same in both directions at any dx . Thus

$$dl_l / I_l = -dl_r / I_r$$

Adding,

$$\frac{dG_l}{G_l} + \frac{dG_r}{G_r} = 2 \frac{d\rho}{\rho}$$

Independent of laser sheet intensity.

* G is gray level, I is laser sheet intensity, ρ is spray mass density, and K is a constant



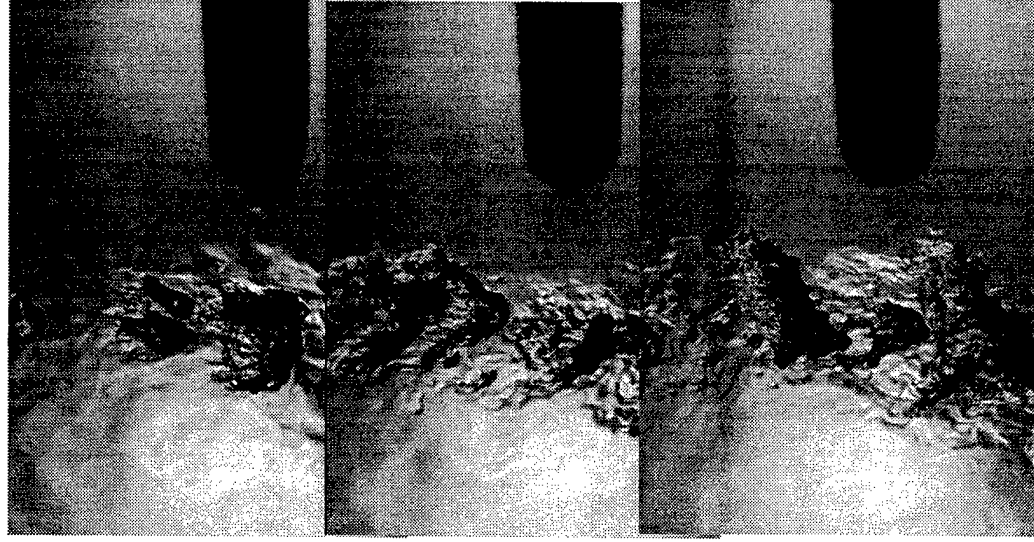
High Pressure and Supercritical Combustion

OBJECTIVE

Determine the mechanisms which control the breakup, transport, mixing, and combustion of high pressure and supercritical droplets, jets, and sprays.

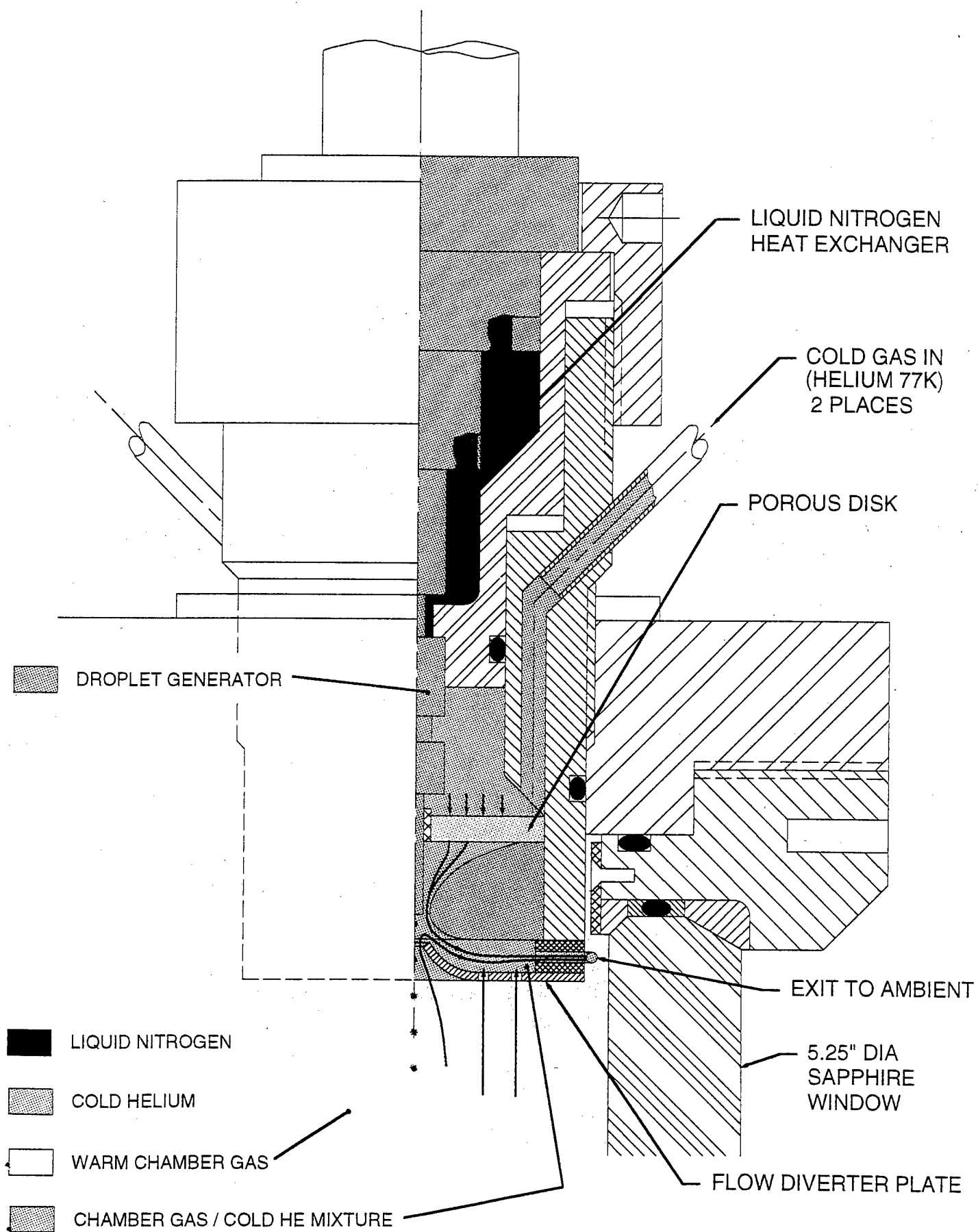
APPROACH

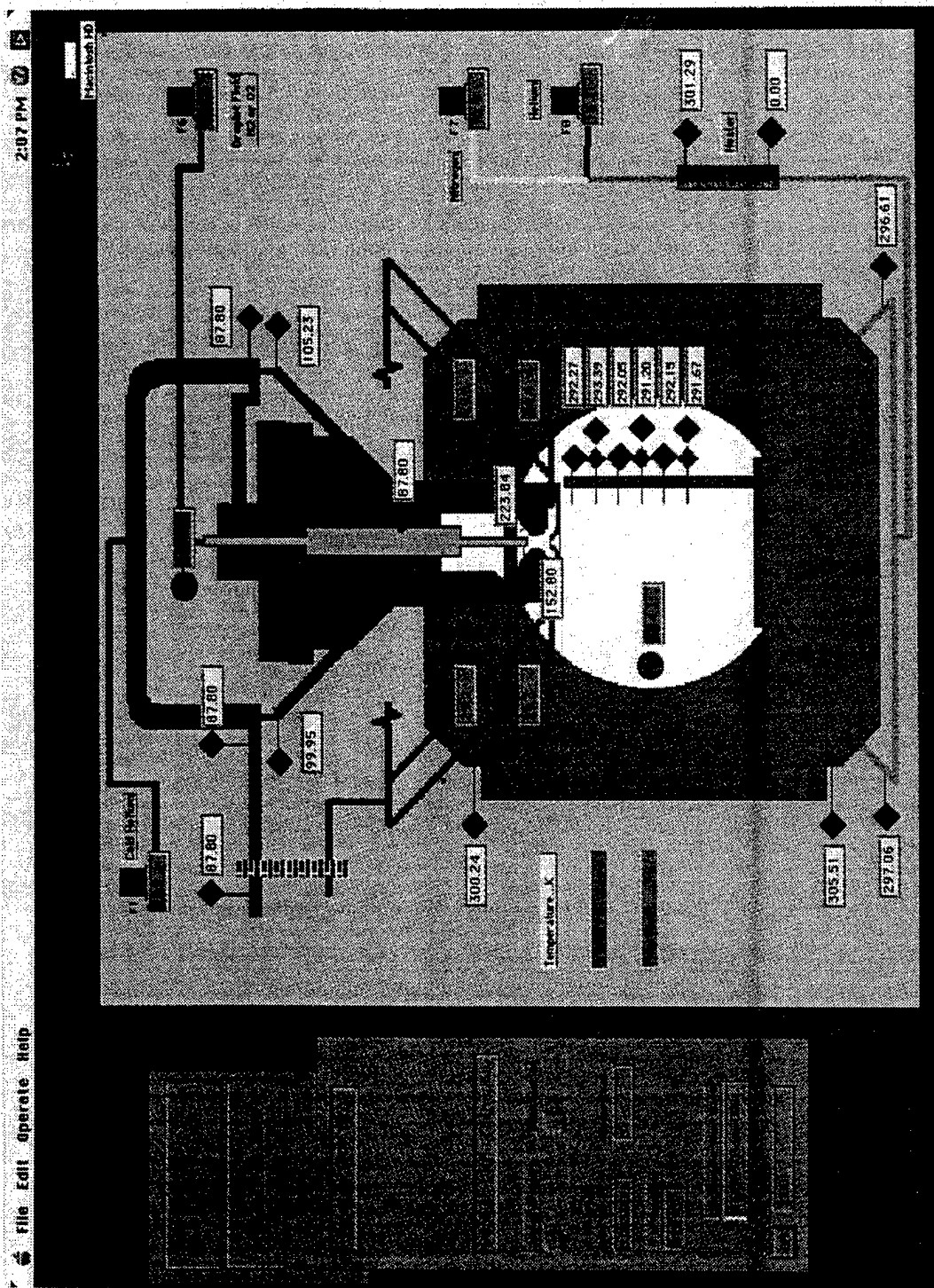
- Working fluids include cryogenics
 - LOX, LN₂
- Droplet studies use *free* droplets to allow realistic deformation and breakup
- Shadowgraph, Schlieren, and planar Raman visualization of concentrations
 - PDPA, Malvern for subcritical cases
- Counter dense sprays/distortions by reducing optical path lengths.



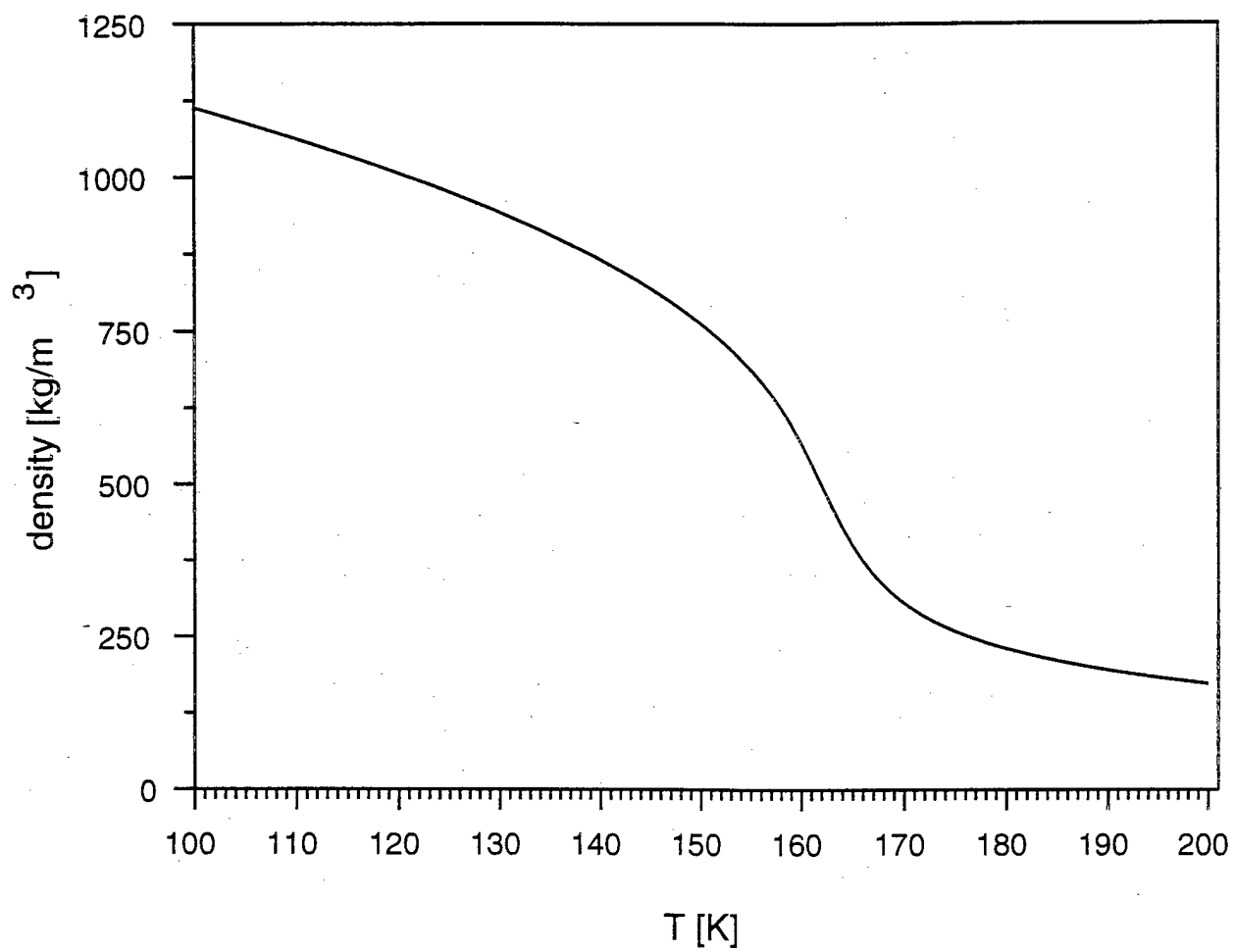
*Transcritical Oxygen Drops
in Nitrogen*

PRESSURE VESSEL / DROPLET GENERATOR INTERFACE





Oxygen Density at 69 atm

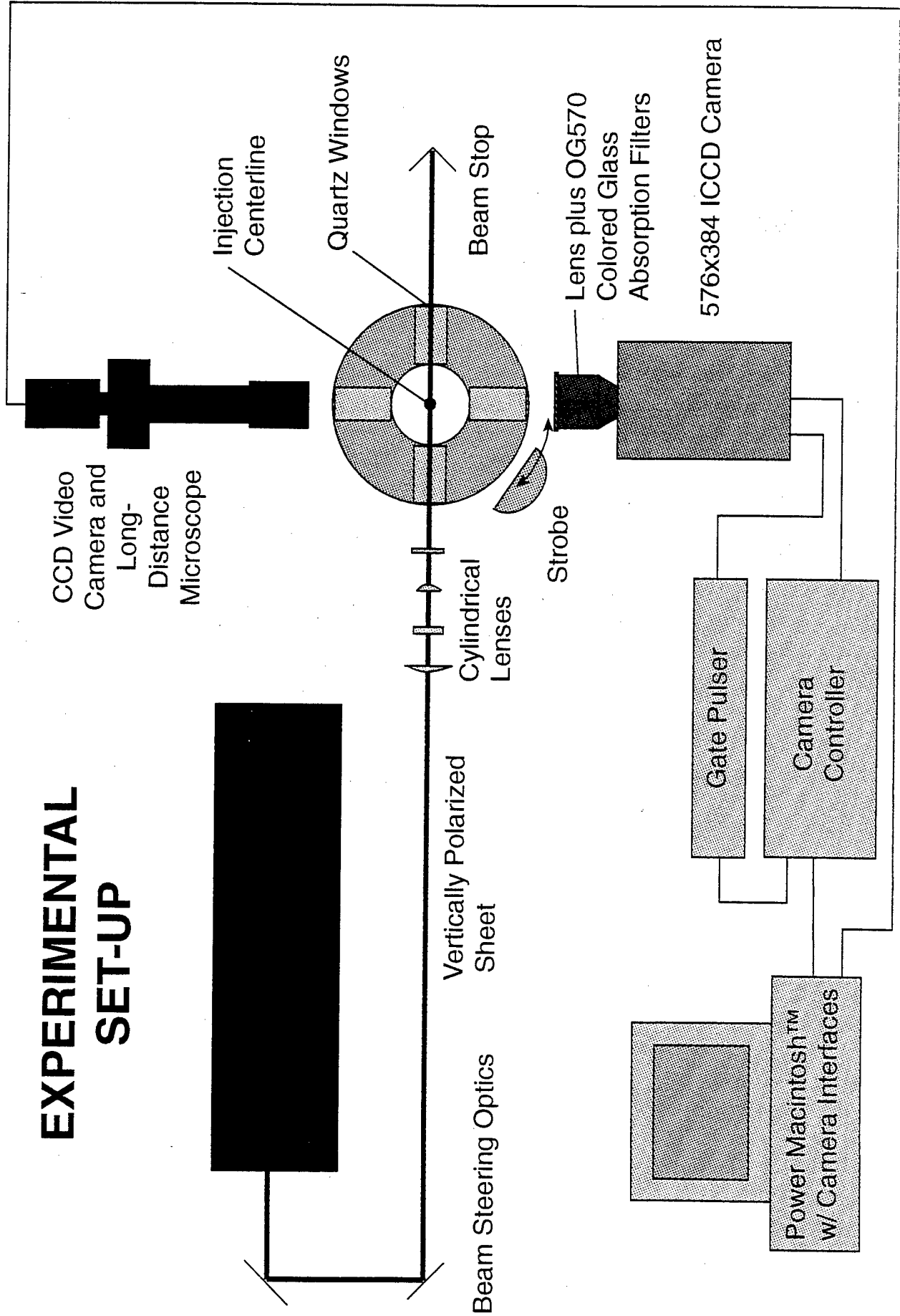




TRANSCRITICAL PROPELLANT INJECTION EXPERIMENTS



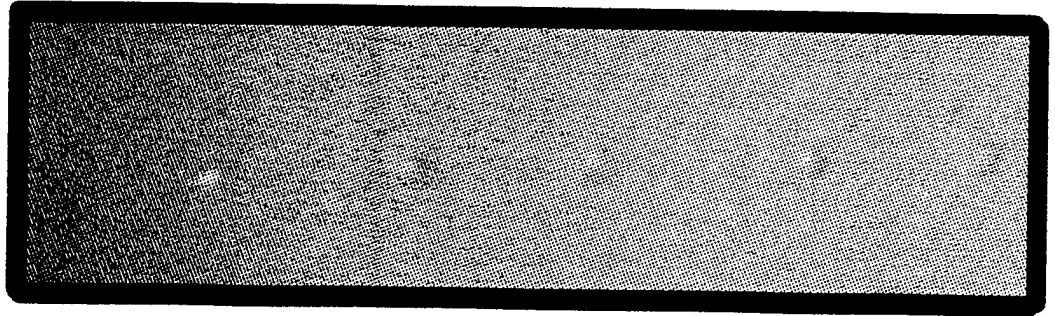
EXPERIMENTAL SET-UP



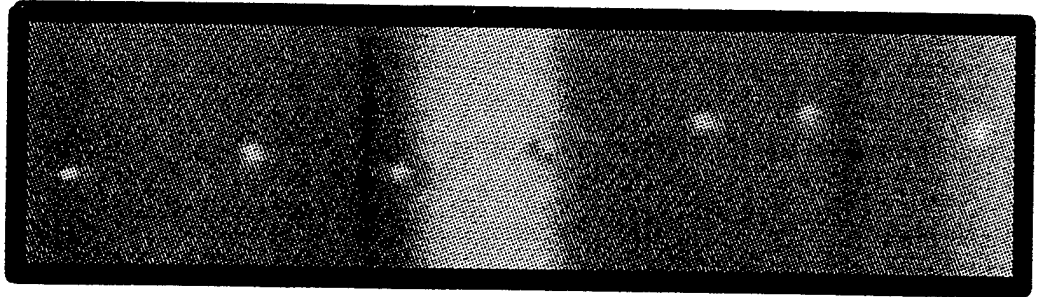


SUPERCritical DROPLET BEHAVIOR LOX DROPLETS INTO HELIUM

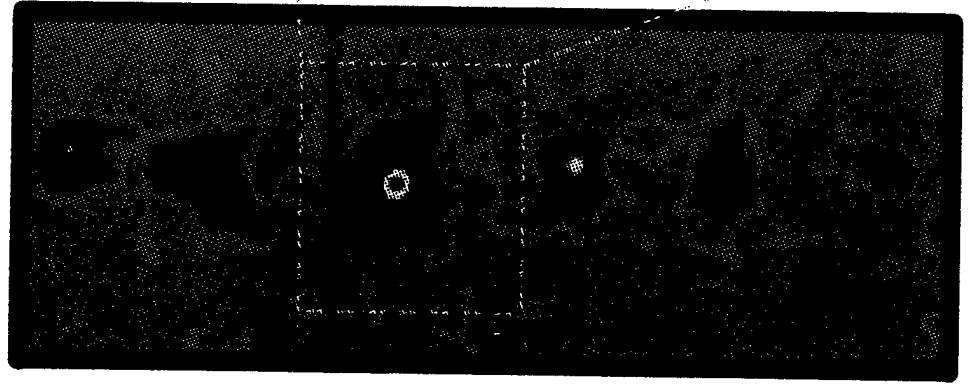
(a) 200 psig



(b) 1000 psig



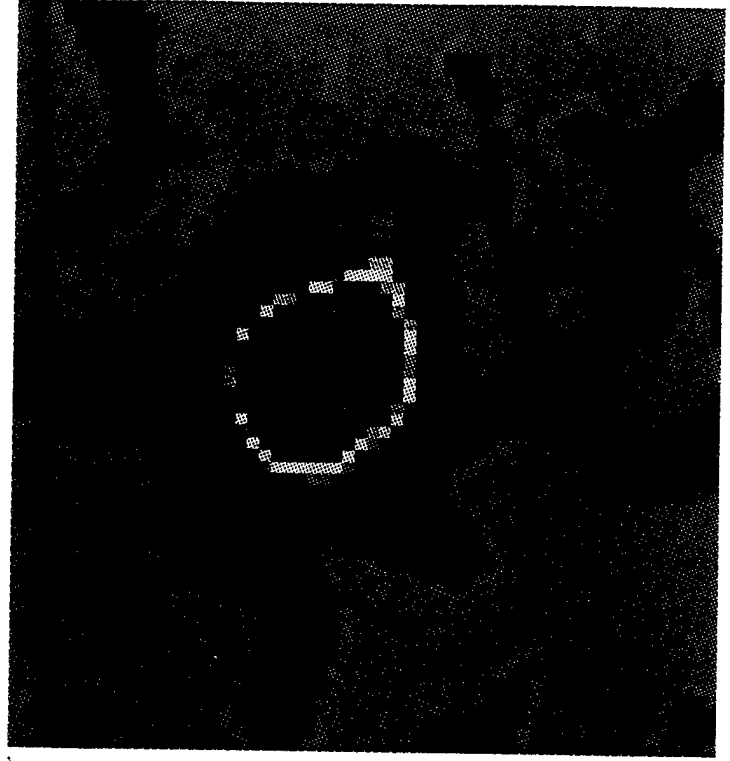
(c) 1000 psig



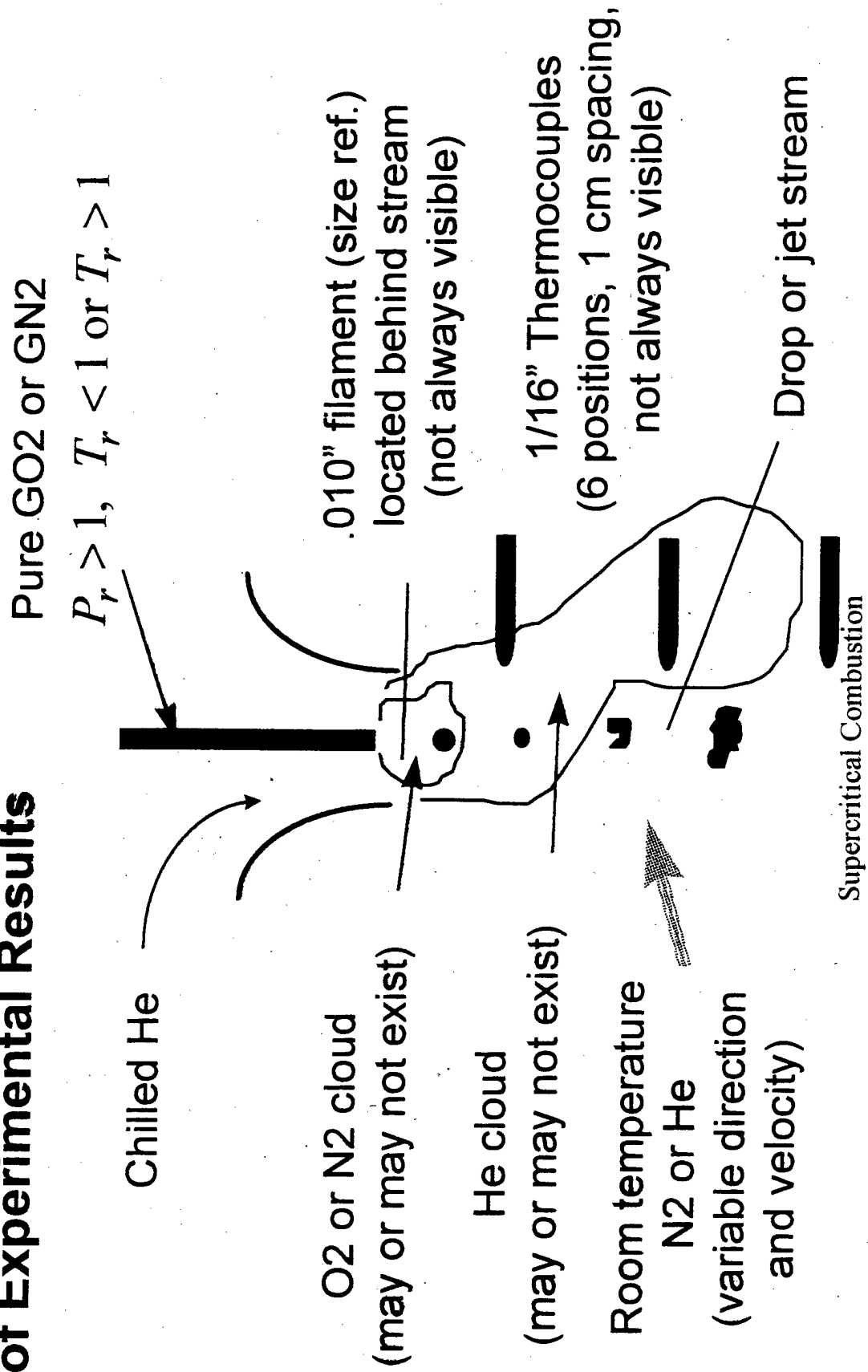
DROP SIZE ~ 200 μm

(a) and (b): Photographs indicate
effect of pressure

(c): Raman imaging shows
non-uniform distribution
of vaporized oxygen

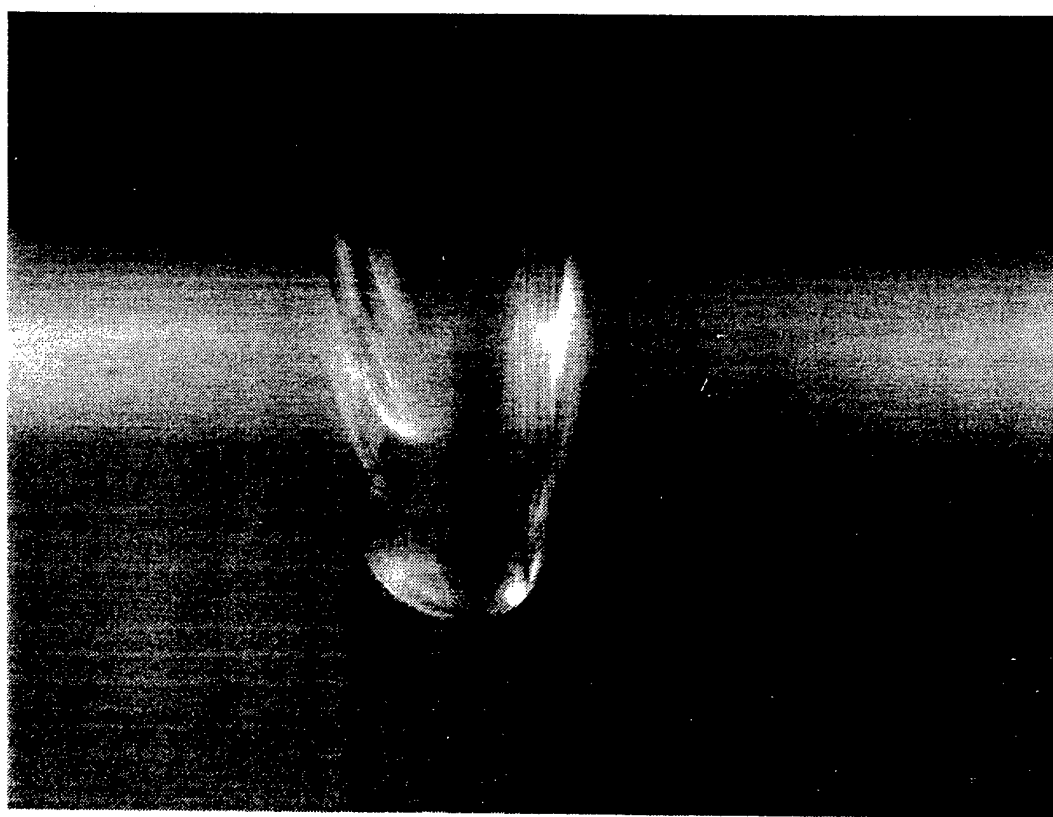


Conceptual Representation of Experimental Results



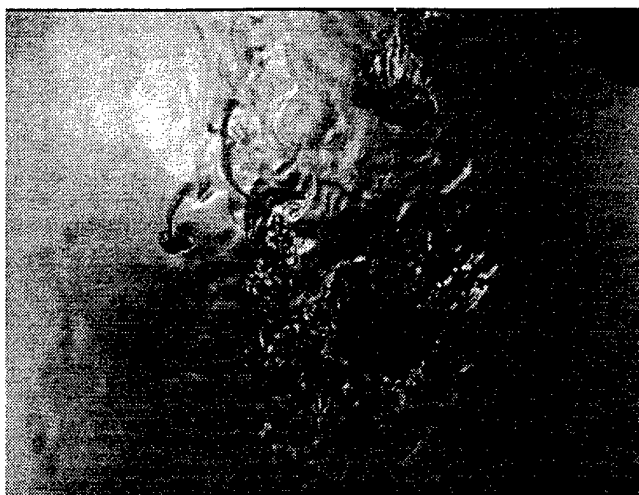
Phillips Laboratory

EXPERIMENTAL RESULTS: Droplets



Supercritical Oxygen Drip through He into N₂ @ 1100 psig

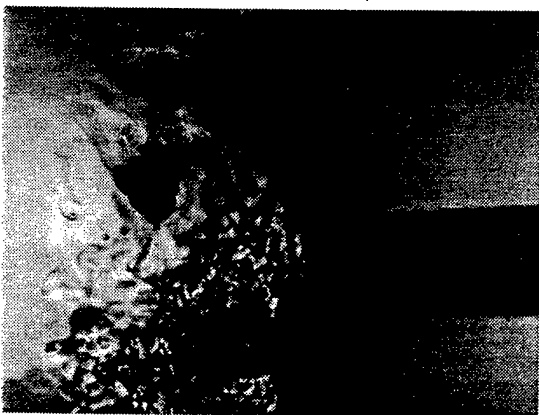
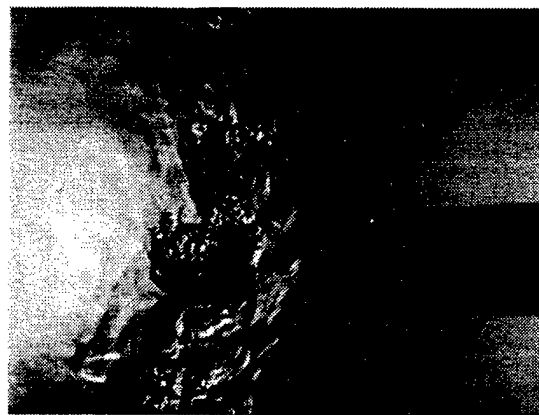
Transcritical Injection of Liquid Oxygen Droplets



Ambient: N₂ @ 970 psig, 290K.
O₂ Injector Temperature: 177K.

Drops formed in chilled helium,
nitrogen flowing across stream.

Sequence corresponds to
increasing distance downstream.



Transcritical Oxygen Drops in N₂ @ 970 psig



Oxygen Droplets Formed in He and Falling into N₂
@ 1000 psig, 280K



Oxygen Droplet Condensation
in Helium @ 1000 psig, 280K

Phillips Laboratory

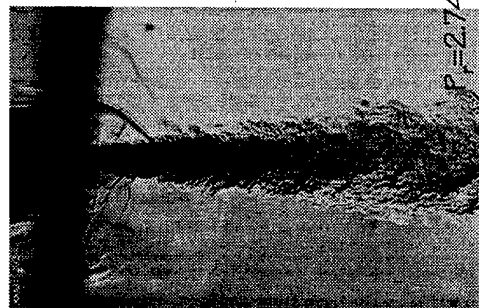
EXPERIMENTAL RESULTS:

Jets

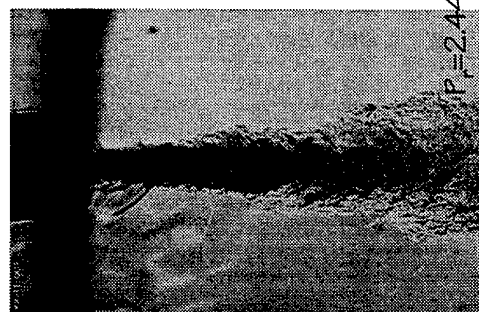


N₂ into N₂

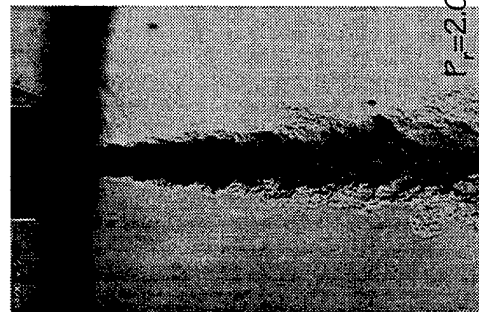
Back-illuminated images of nitrogen injected into nitrogen at a fixed supercritical temperature of 300 K but varying sub- to supercritical pressures. $P_r = P_{ch}/P_{critical}$. $Re = 25,000$ to $75,000$. Injection velocity: 10-15 m/s. Froude number: 40,000 to 110,000. Injectant temperature: 99 to 120 K.



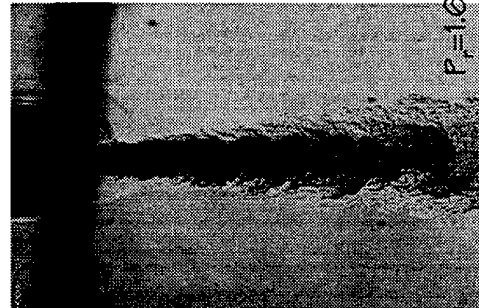
$P_r = 2.74$



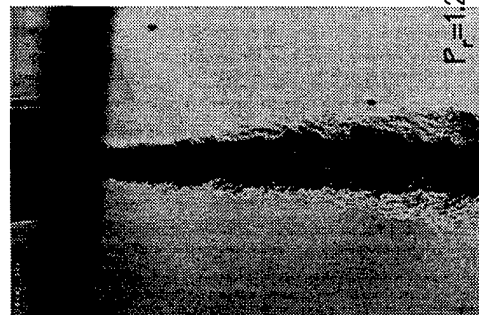
$P_r = 2.44$



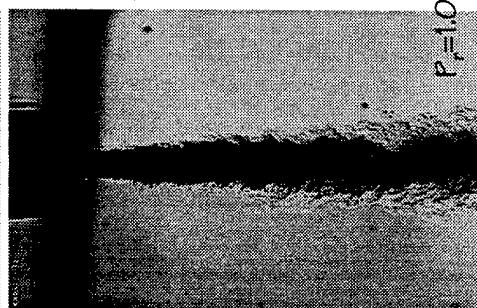
$P_r = 2.03$



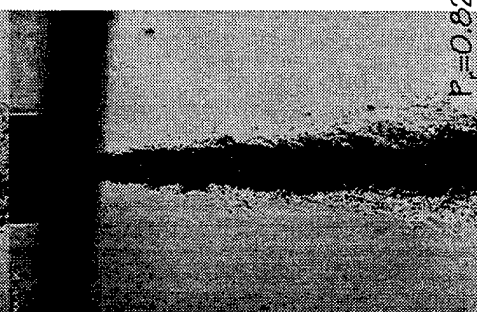
$P_r = 1.62$



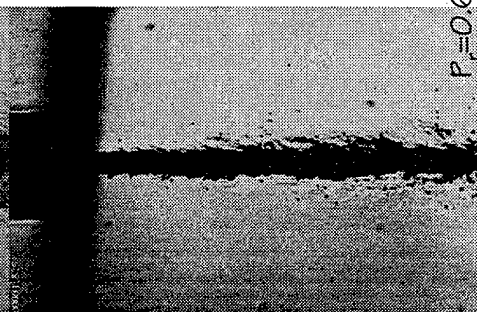
$P_r = 1.22$



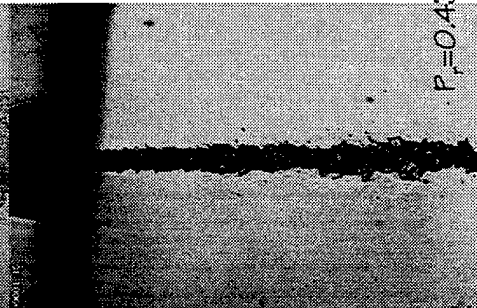
$P_r = 1.03$



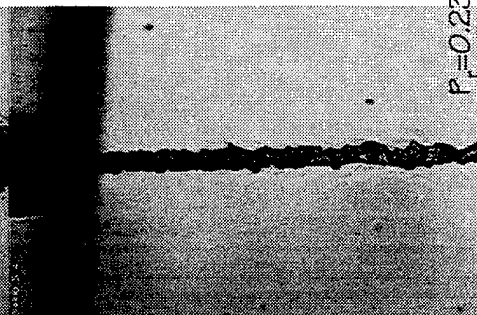
$P_r = 0.82$



$P_r = 0.62$



$P_r = 0.43$



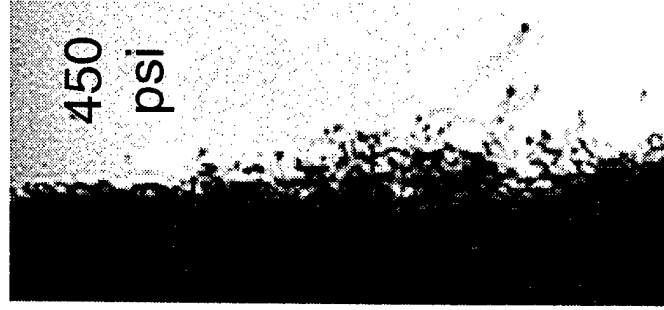
$P_r = 0.23$



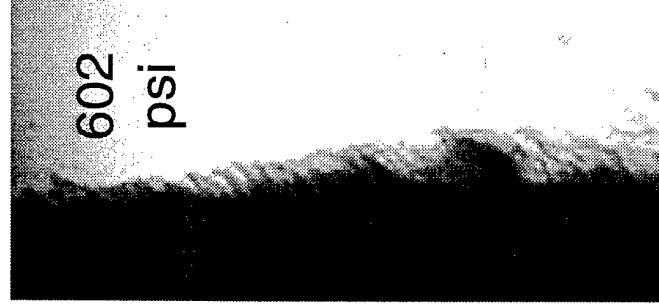
PRESSURE DEPENDENT MIXING LAYER STRUCTURE

Nitrogen/nitrogen system ($P_{cr} = 493$ psi, $T_{cr} = 126$ K)

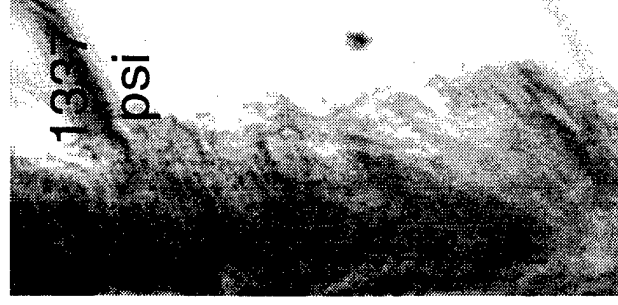
$T_{inj} = 128$ K, $T_{amb} = 300$ K, mass flow = 350 mg/s



***Low Pres.
Subcritical
Droplets***



***Mod. Pres.
Supercritical
Ligaments***



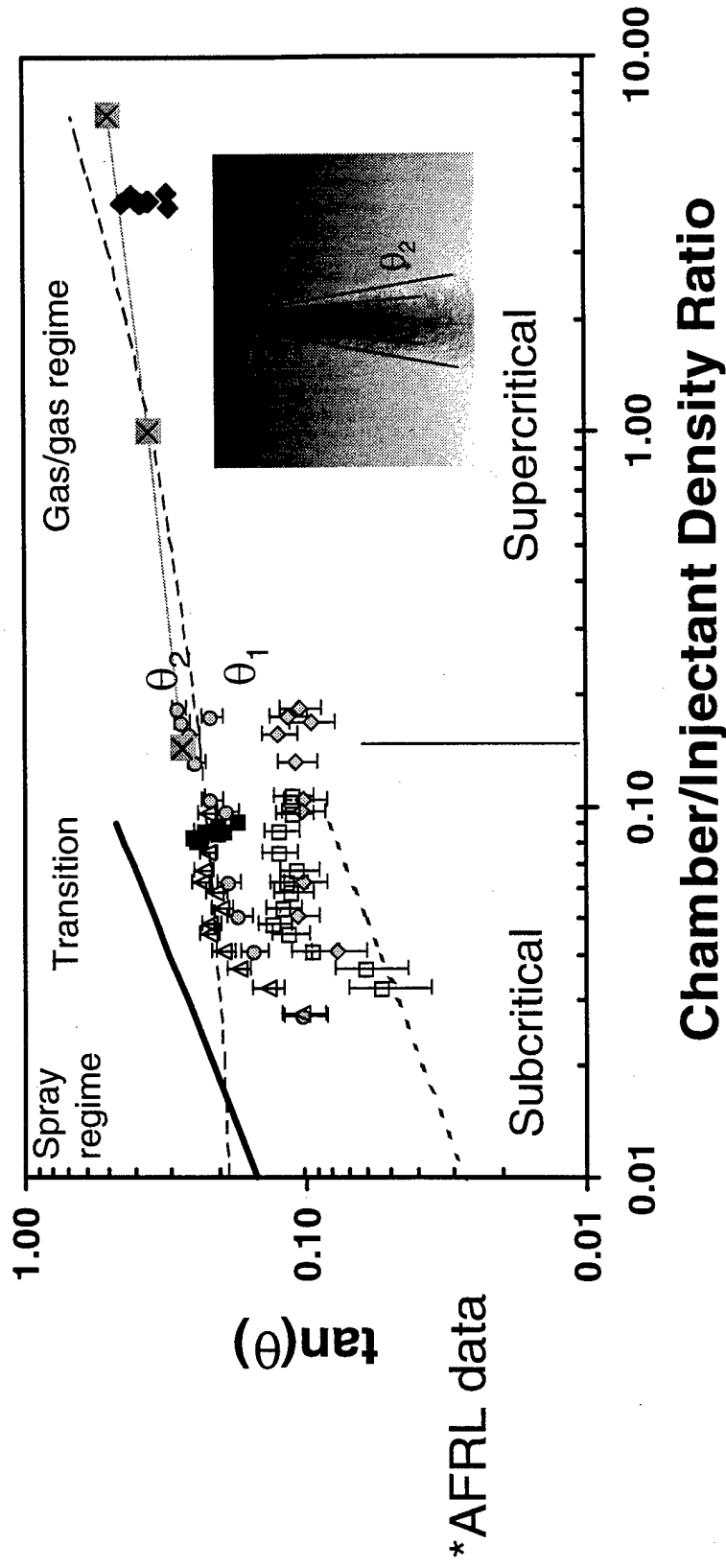
***High Pres.
Supercritical
Gas layers***

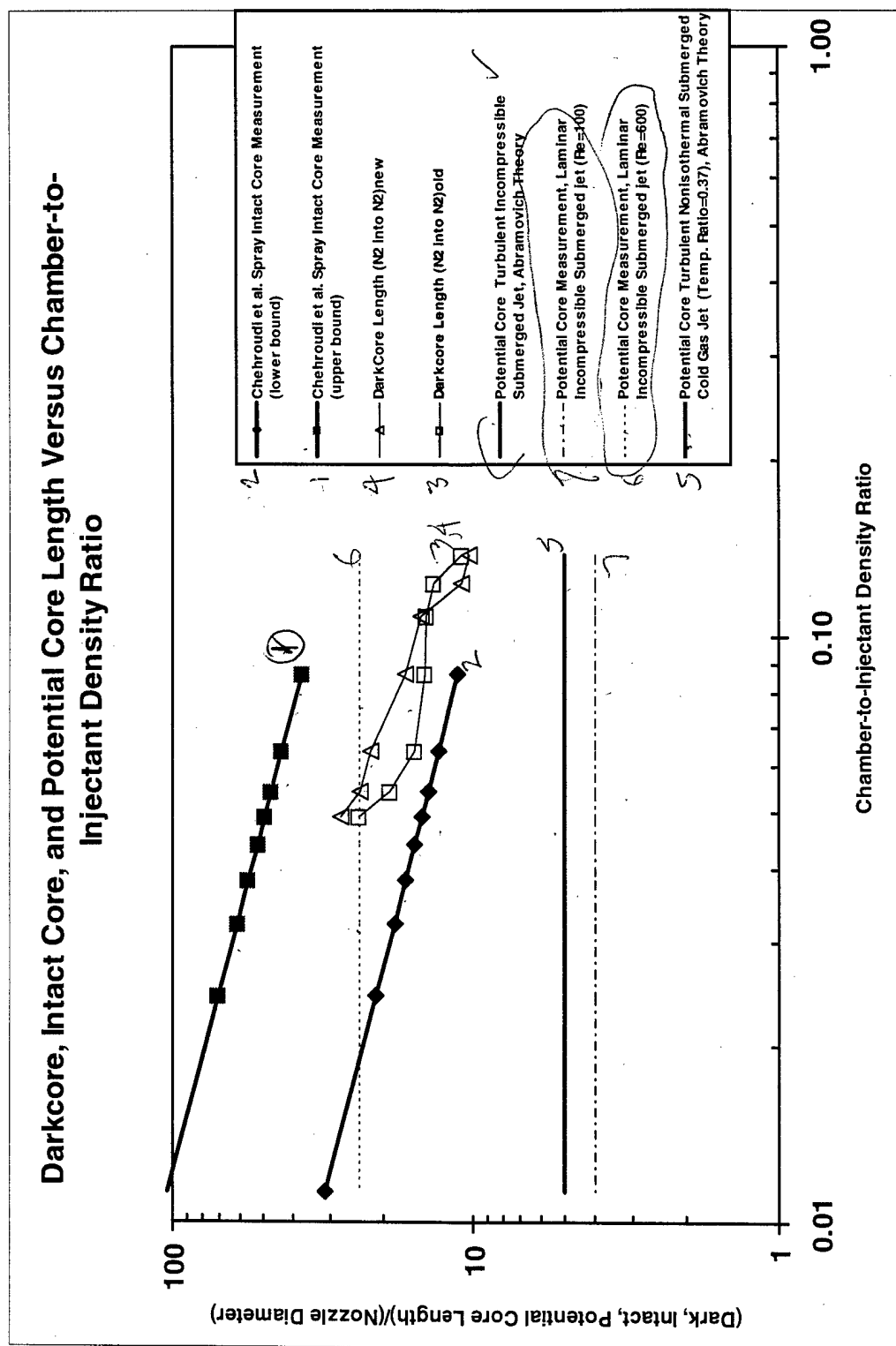
Air Force Research Laboratory

(6.1)

Sub- and Super-critical Mixing Layer Physics

- Steady Diesel-Type Spray $L/D=4$ - - - Steady Diesel-Type Spray $L/D=85$ ○ N2 jet into N2 $L/D=200$ (*)
- ◇ N2 jet into N2 Darkcore (*) ◆ Cold He jet into N2; $L/D=200$ (*) ■ Cold N2 jet into He; $L/D=200$ (*)
- Brown & Roshko (He/N2) △ O2 jet into N2; $L/D=200$ (*) □ O2 jet into N2; Darkcore (*)
- - - Theory (Papamoschou & Roshko)





Characteristic Times

- Characteristic bulge formation time (τ_b) at the jet interface (Tseng et al.): $(\rho_l L^3 / \sigma)^{1/2}$; ρ_l , L , σ are liquid density, characteristic dimension of turbulent eddy, and surface tension, respectively.
- Characteristic time for gasification (τ_g) (D-square law): D^2/K ; D and K are drop diameter and vaporization constant.
- A Hypothesis: If these two characteristic times (calculated for appropriate length scales) are comparable then an interface bulge may not be separated as an unattached entity (onset of the gas-jet behavior at supercritical condition)

Similar equation format for different

cases

- Theoretical isothermal liquid spray growth rate (θ_s) based on Orr-Sommerfeld equation and stability analysis to find the wavelength of the most unstable interface wave:

$$\theta_s \cong 0.27 [0 + (\rho_g/\rho_l)^{0.5}]$$

- Papamoschou/Rashko theory for incompressible variable-density gaseous mixing layer/jet:

$$\theta_{P/R} \cong 0.17 [1 + (\rho_g/\rho_l)^{0.5}]$$

- Dimotakis theory for incompressible variable-density gaseous mixing layer/jet:

$$\theta_d \cong 0.212 [0.59 + (\rho_g/\rho_l)^{0.5}]$$

- ALL HAVE THE SQUARE ROOT OF DENSITY RATIO AND THE SAME EQUATION FORMAT

Proposed “intuitive/smart” equation

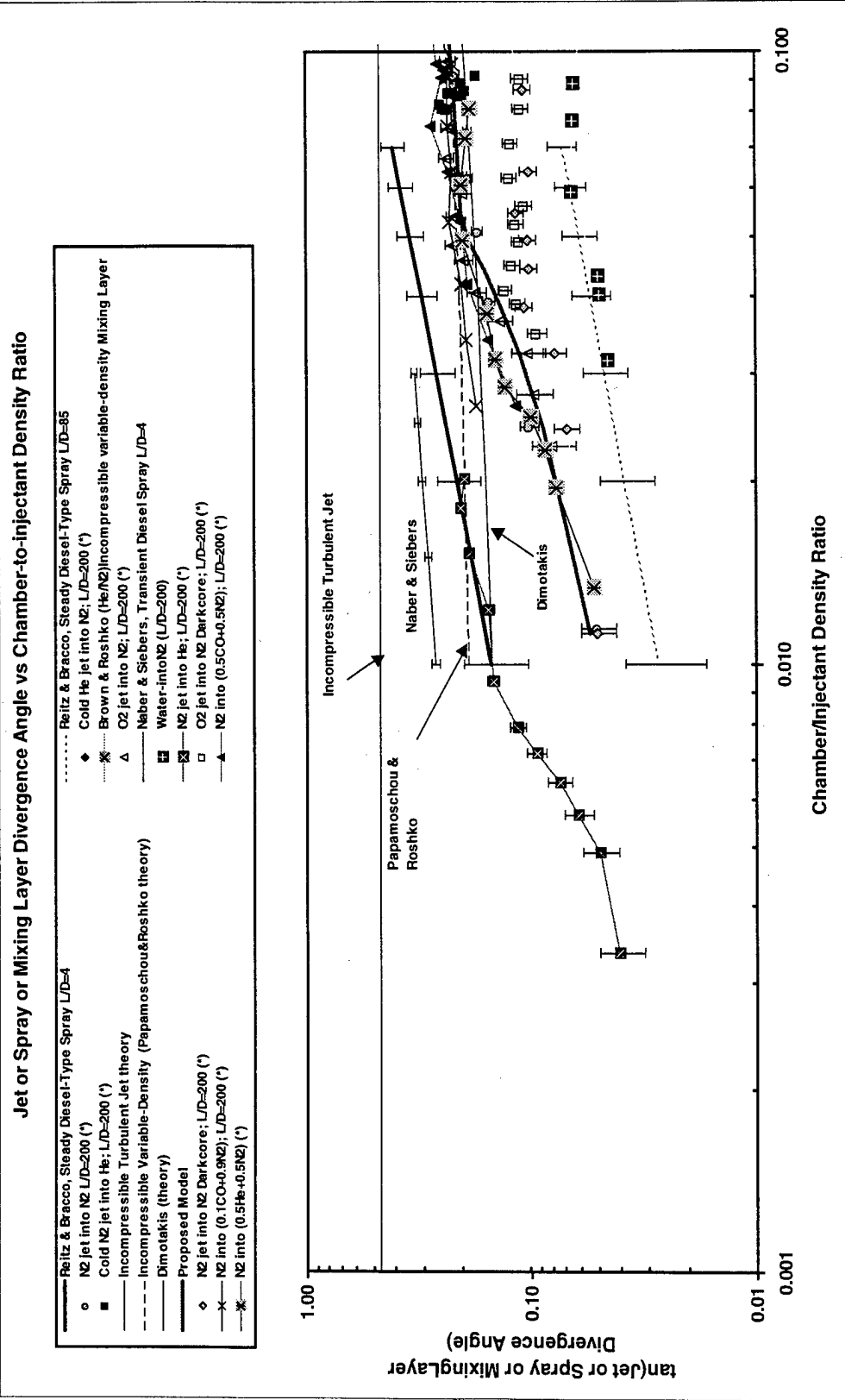
- Based of the information of the previous slide the following “intuitive/smart” equation is proposed for both sub- and supercritical measured growth rates:

$$\theta_{ch} \cong 0.27 [(\tau_b/(\tau_b + \tau_g)) + (\rho_g/\rho_l)^{0.5}]$$

Note:

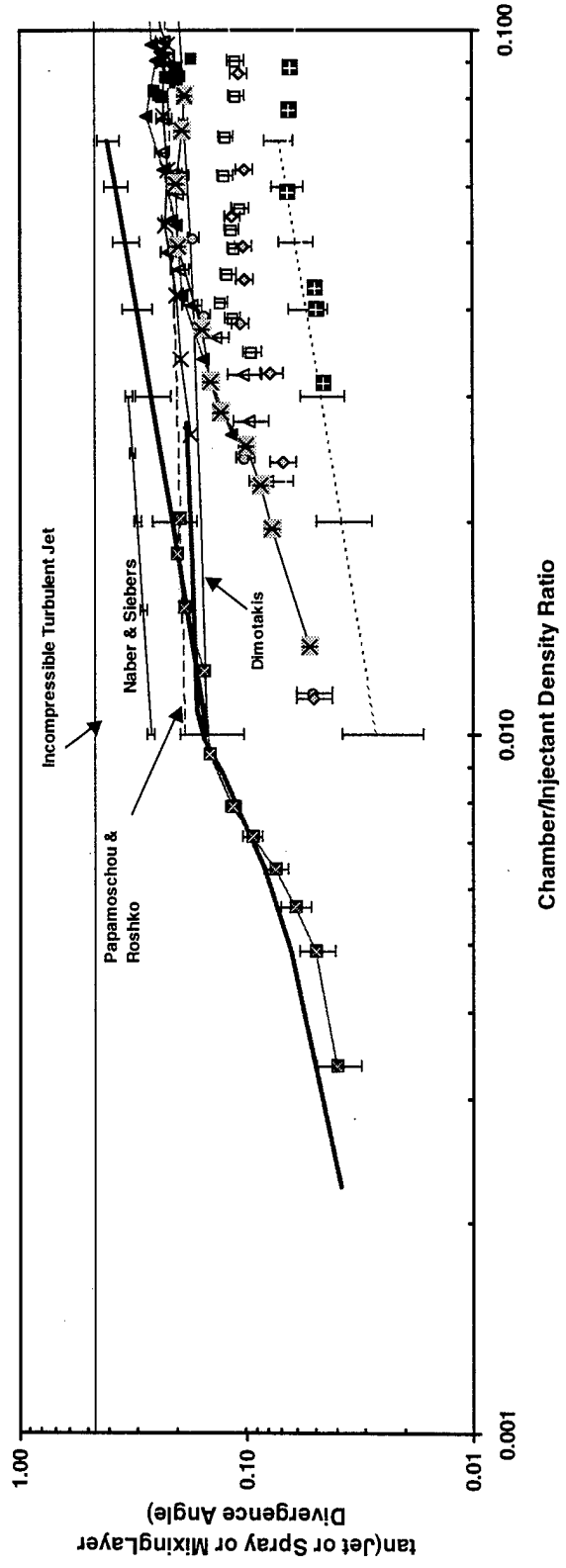
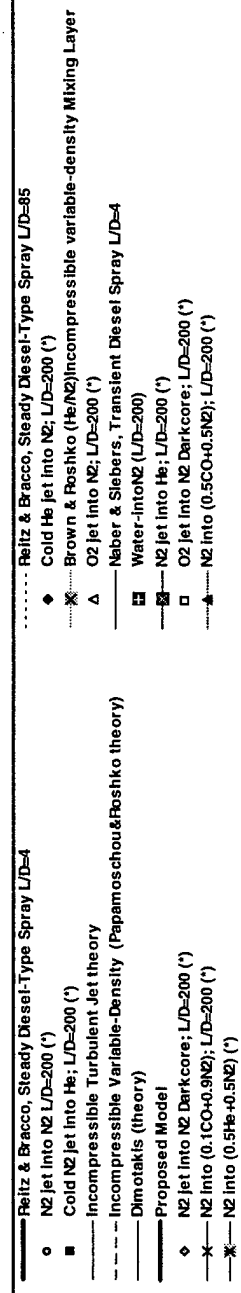
- For isothermal liquid case: $\tau_g \gg \tau_b$ and $\tau_g \rightarrow \infty$. It then collapses to the isothermal spray case.
- For subcritical the $(\tau_b/(\tau_b + \tau_g))$ is calculated until it reaches 0.5. After that it is maintained constant at 0.5n for supercritical jet. The transition point is found to be approximately when $(\tau_b/(\tau_b + \tau_g)) \cong 0.5$.
- Only a horizontal axis variable transformation is needed to fit with the N₂-into-He experimental growth rate data.

Comparison of the proposed equation (solid red line) with experimental data



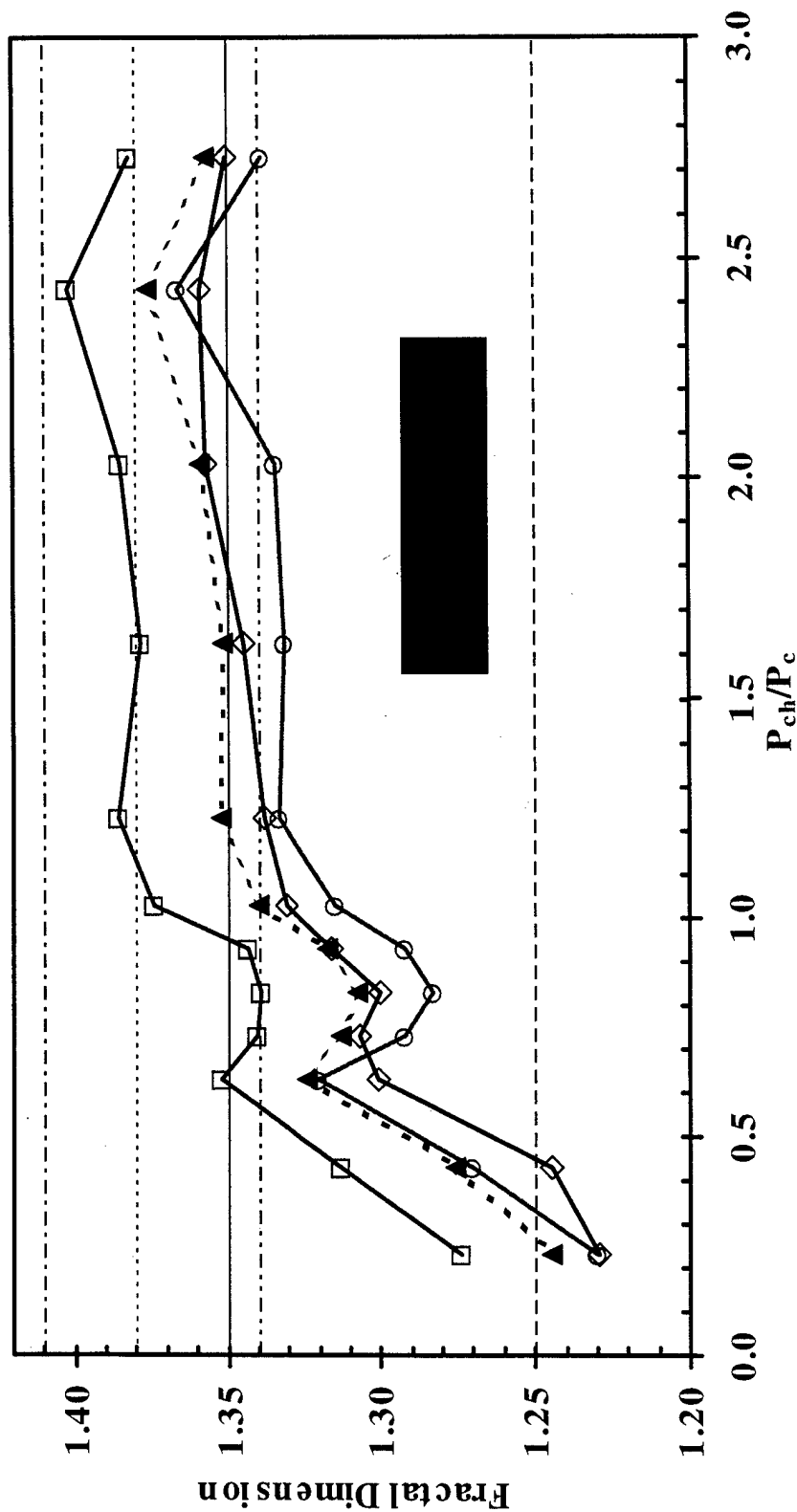
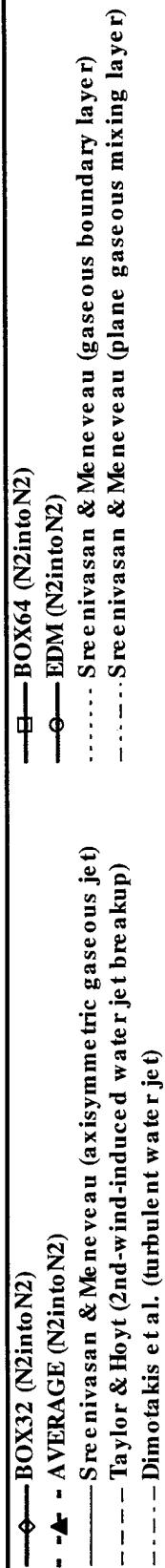
Comparison of the proposed "intuitive/smart" equation with the N₂-into-He experimental data

Jet or Spray or Mixing Layer Divergence Angle vs Chamber-to-injectant Density Ratio





FRACTAL DIMENSION vs. RELATIVE PRESSURE



Instant images of Sub- and Supercritical impinging jets

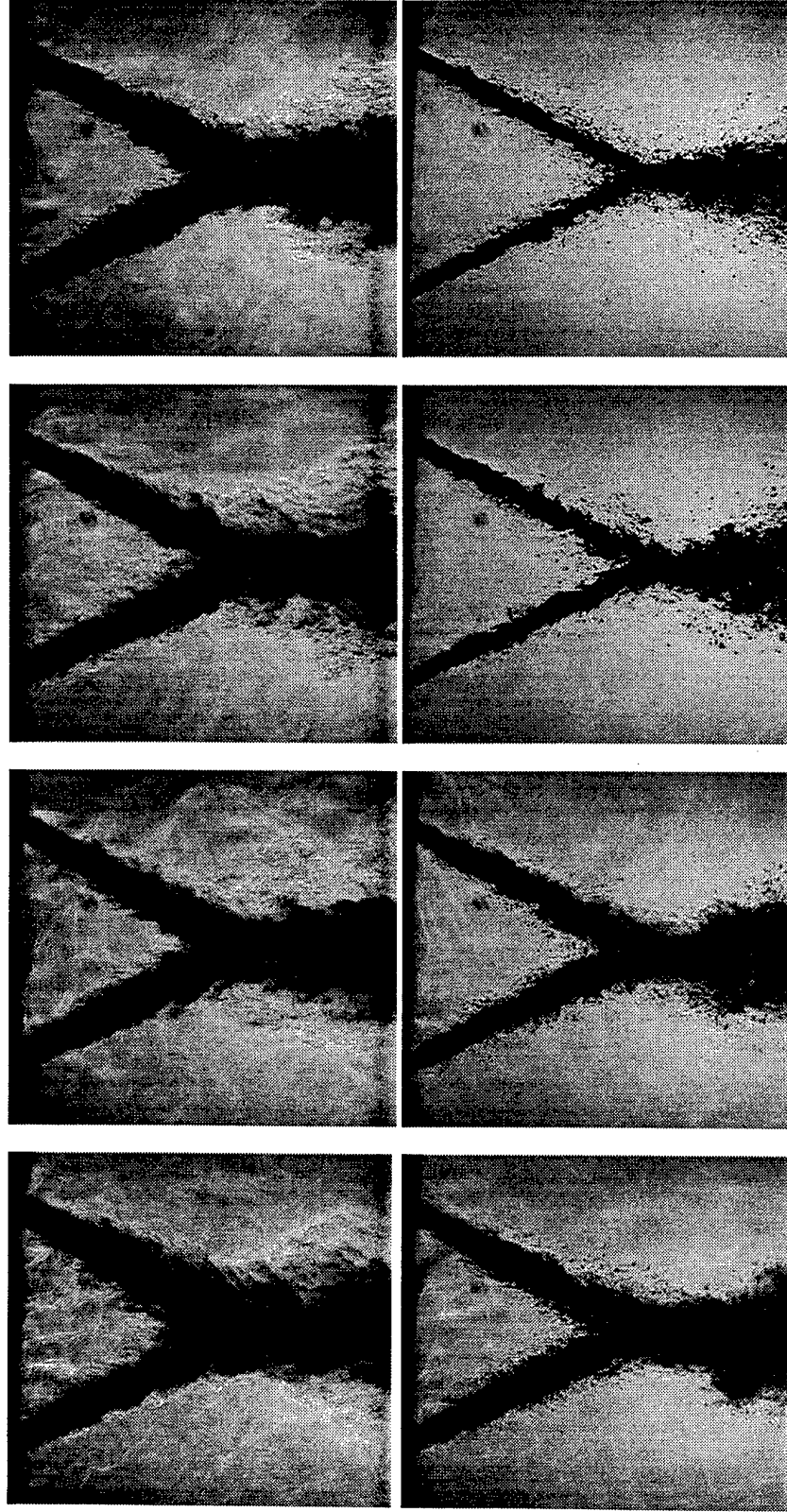
N_2 into N_2

($P_{critical} = 3.39 \text{ MPa}$; $T_c = 126.2 \text{ K}$)

($P_{ch} = 800, 600, 500, 400, 350, 300, 200, 100 \text{ psig}$; from upper left to lower right)

($P_{ch} = 5.5, 4.2, 3.5, 2.8, 2.5, 2.1, 1.5, 0.8 \text{ MPa}$; from upper left to lower right)

($Re = 25,000$ to $70,000$; injection velocity: $10\text{--}15 \text{ m/s}$)



Instant images of Sub- and Supercritical impinging jets

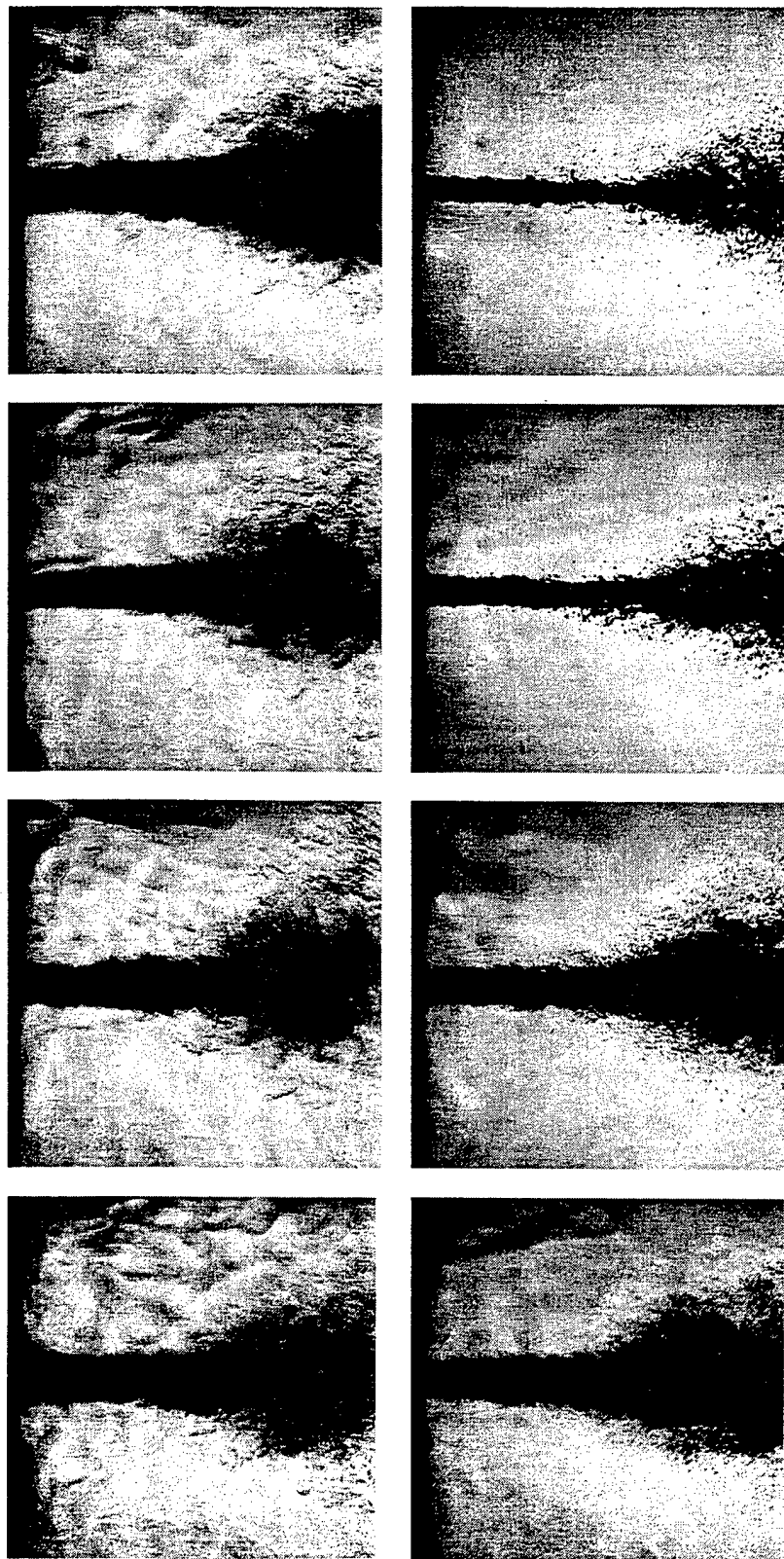
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Summary and Conclusions

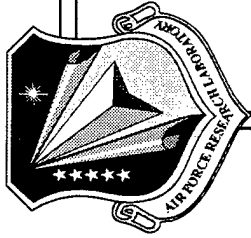
- Cryogenic Jet structural differences are observed below and above the thermodynamic critical point.
- Liquid-Jet like appearance up to near critical point similar to second wind-induced liquid jet breakup regime.
- Gas-jet like appearance above the critical point. No drops are observed.
- A unique plot has been constructed for the jet growth rate covering density ratio range of up to a 1000.
- Measured growth rate (divergence angle) of our cryogenic jet under supercritical condition agrees well with the theoretical equations by Papamoschou & Roshko and Dimotakis for incompressible variable-density turbulent gaseous mixing layer.

method of



Summary and Conclusions (cont.)

- Transition to full atomization regime is inhibited due to vanishingly small surface tension and heat of vaporization.
- All tend to strengthen the position that jets under the condition investigated here exhibit gas-jet like behavior at near and above the critical point of the injectant. Here the gas-jet like behavior is quantitatively demonstrated and verified for the first time.
- The relevancy of current injection models and some drop vaporization/combustion results under the conditions where gas-jet like behavior is detected should be reexamined.



Basic Research Opportunities

1990's at AFRL

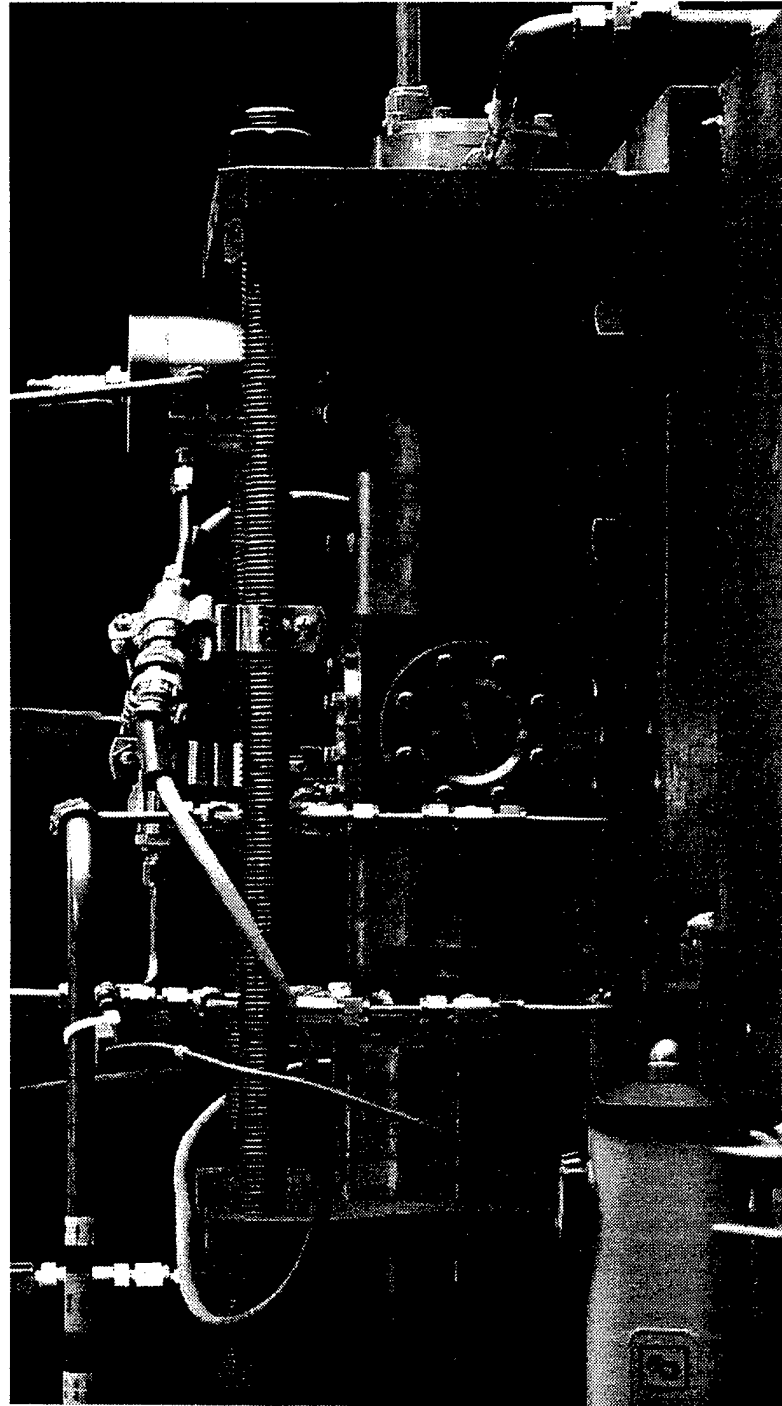
- High pressures, “steady.”
- Gas/gas injection

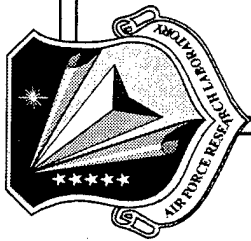
Future

- Injector/chamber interactions
- Transients
 - Organized
 - Un-organized
- Revolutionary cycles
 - Pulsed detonation propulsion
 - Combined cycle



Gas/gas hardware

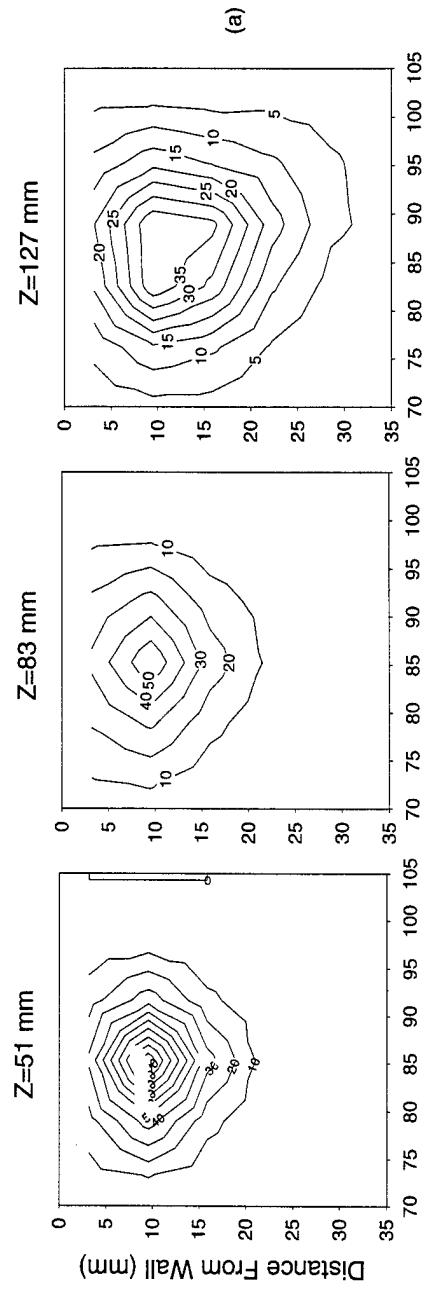




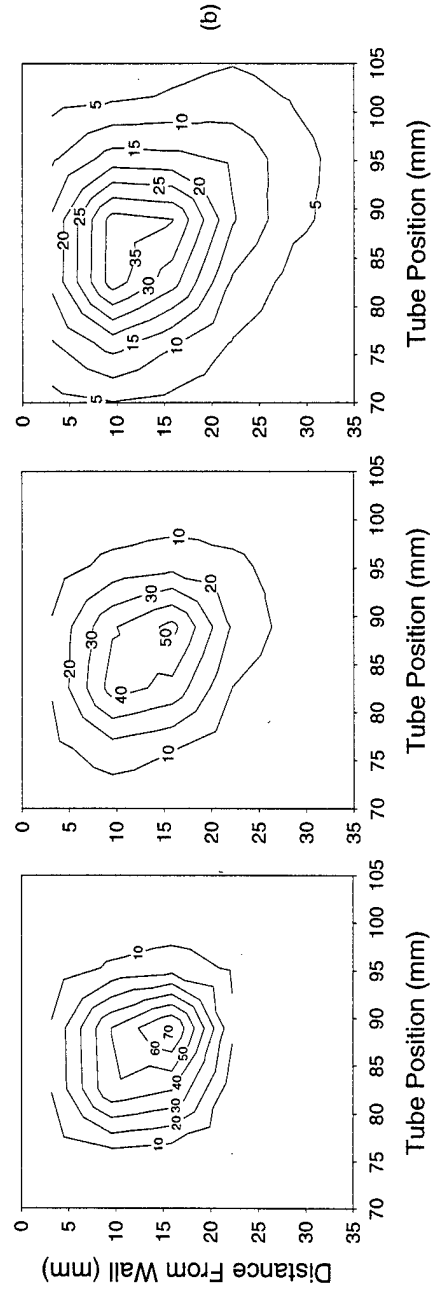
LOX post biasing study

Water/N₂, density ratio = 117

Unbiased



Biased





Pulsed Detonation Rocket Engine Test at AFRL

