

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY)

2. REPORT TYPE

Technical Paper

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

2308

5e. TASK NUMBER

M13C

5f. WORK UNIT NUMBER

346057

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

11. SPONSOR/MONITOR'S NUMBER(S)

Please see attached

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20030116 055

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

a. REPORT

Unclassified

b. ABSTRACT

Unclassified

c. THIS PAGE

Unclassified

17. LIMITATION OF ABSTRACT

A

18. NUMBER OF PAGES

19a. NAME OF RESPONSIBLE PERSON

Leilani Richardson

19b. TELEPHONE NUMBER

(include area code)
(661) 275-5015

MEMORANDUM FOR PR (In-House Contractor/In-House Publication)
FROM: PROI (TI) (STINFO)

29 February 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-038**
Chchroudi, B. (ERC), Badakshan, A., Cohn, R., Talley, D., "Injection of Cryogenic Fluids into Subcritical and Supercritical Environments"

Invited University Seminar (Statement A)
Eidgenossische Technische Hochschule (ETH), Zurich, Switzerland
17 Mar 2000 (**Absolute Deadline: 09 Mar 2000**)

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.

Comments: _____

Signature _____ Date _____

2. This request has been reviewed by the Public Affairs Office for: a.) appropriateness for public release and/or b) possible higher headquarters review.

Comments: _____

Signature _____ Date _____

3. This request has been reviewed by the STINFO for: a.) changes if approved as amended, b.) appropriateness of distribution statement, c.) military/national critical technology, d.) economic sensitivity, e.) parallel review completed if required, and f.) format and completion of meeting clearance form if required

Comments: _____

Signature _____ Date _____

4. This request has been reviewed by PR for: a.) technical accuracy, b.) appropriateness for audience, c.) appropriateness of distribution statement, d.) technical sensitivity and economic sensitivity, e.) military/national critical technology, and f.) data rights and patentability

Comments: _____

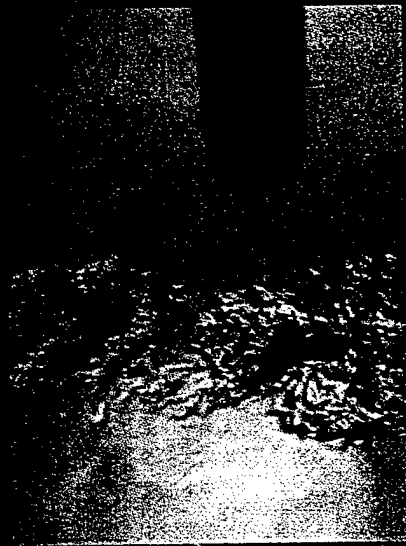
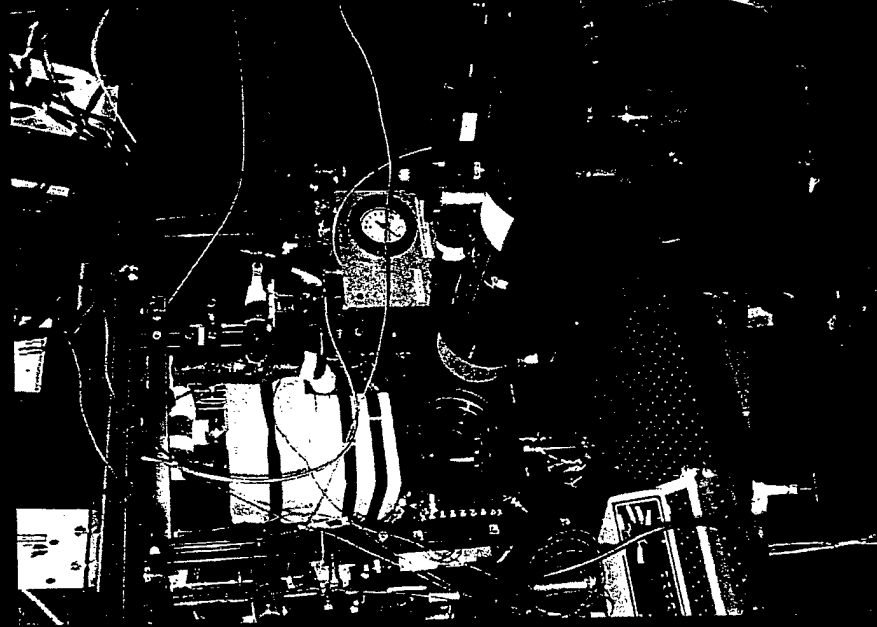
APPROVED/APPROVED AS AMENDED/DISAPPROVED

ROBERT C. CORLEY (Date)
Senior Scientist (Propulsion)
Propulsion Directorate



Injection of Cryogenic Fluids into Subcritical and Supercritical Environments

Doug Talley
Group Leader, Rocket Combustion Devices
Air Force Research Laboratory



Credits

AFRL

Principle Investigators

- Dr. Bruce Chehroudi
- Dr. Roger Woodward

Collaborators

- R. Cohn
- E. Coy
- A. Badakshan
- D. Poulidakos

Motivation

AFRL

At Edwards

- Supercritical conditions that can exist inside rocket engines

Other

- Gas turbines
- Diesel
- etc



Space Shuttle Main Engine
LOX/H₂, 500,000 lb thrust (112,000 N)

The Problem

AFRL

- It is often advantageous to operate combustion chambers at pressures exceeding the critical pressure of one or both propellants.
 - Higher chamber pressures lead to greater performance (Isp).
- At supercritical pressures, the distinct difference between gas and liquid phases disappears.
 - Conventional “spray combustion” experience no longer applies.
- It is not known how to replace conventional “spray combustion” models in engine design codes.
 - *The lack of understanding leads to potentially large engine design errors.*

The Problem (3)

AFRL

Other factors not normally considered in conventional spray combustion

- Vanishing surface tension and enthalpy of vaporization.
- Equivalent “gas” and “liquid” phase densities.
- Strongly enhanced solubility of one species (“gas”) into another (“liquid”).
- Reduced gas phase diffusivity (more liquid-like).
- Large property excursions near the critical point
 - Conductivity, viscosity, speed of sound, specific heats.
- Mixing induced critical point variations.
- Enhanced gas phase unsteadiness.
- Potentially different kinetics mechanisms.

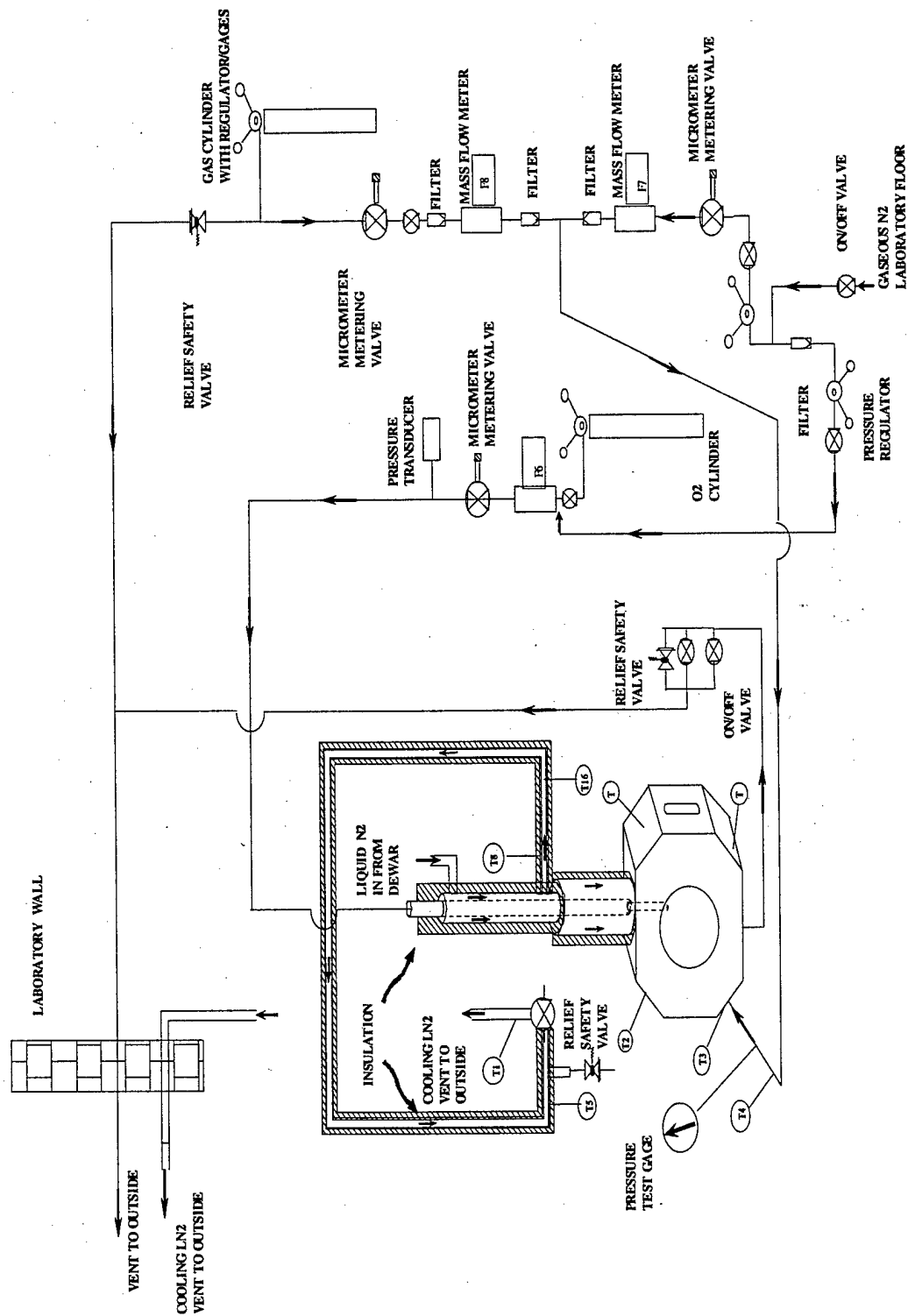
Objectives

AFRL

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

Experimental Set-up

AFRI

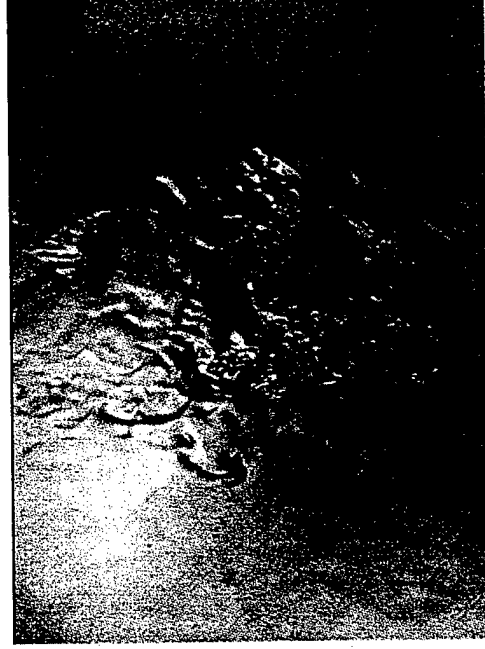


Transcritical LOX drops in room temperature GN2

AFRL



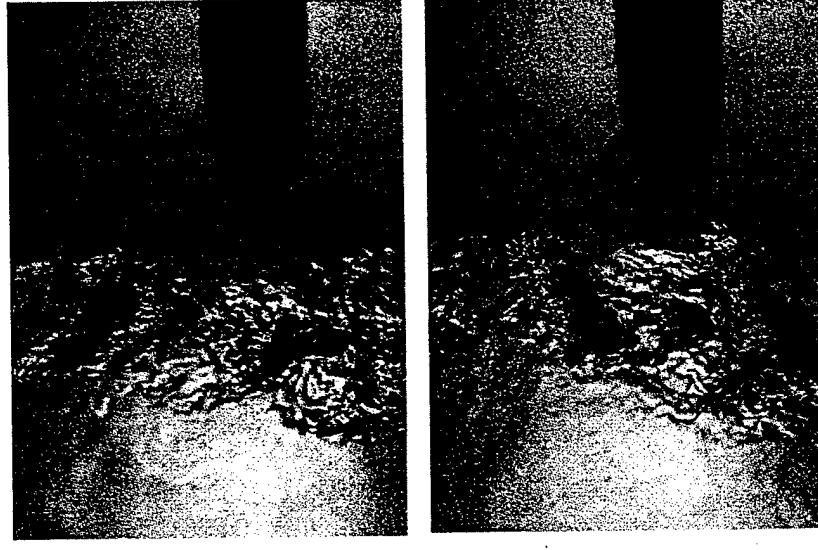
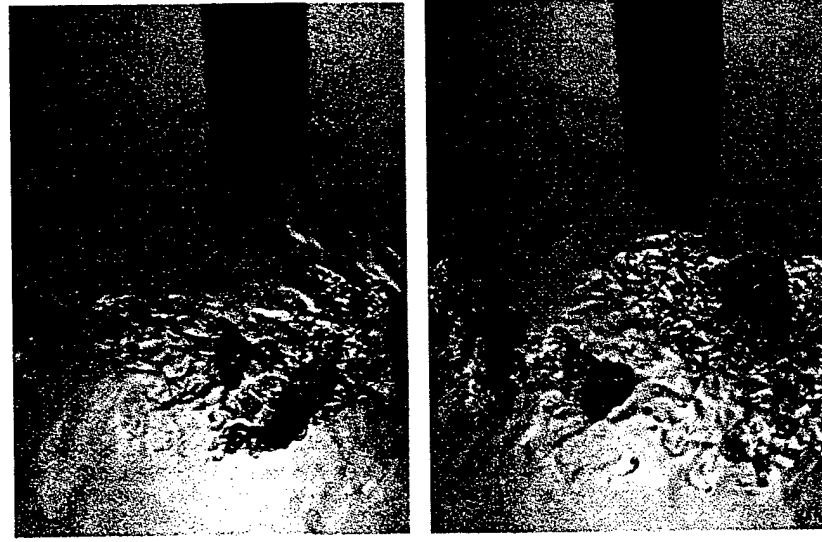
1/16" (1.6 mm)



Representative evolution of transcritical drop disintegration

Transcritical LOX drops in room temperature GN2 (2)

AFRL



Visualization at different times at the same location

Shadowgraph Results - N₂ into N₂

$P_{cr} = 3.39 \text{ MPa}$

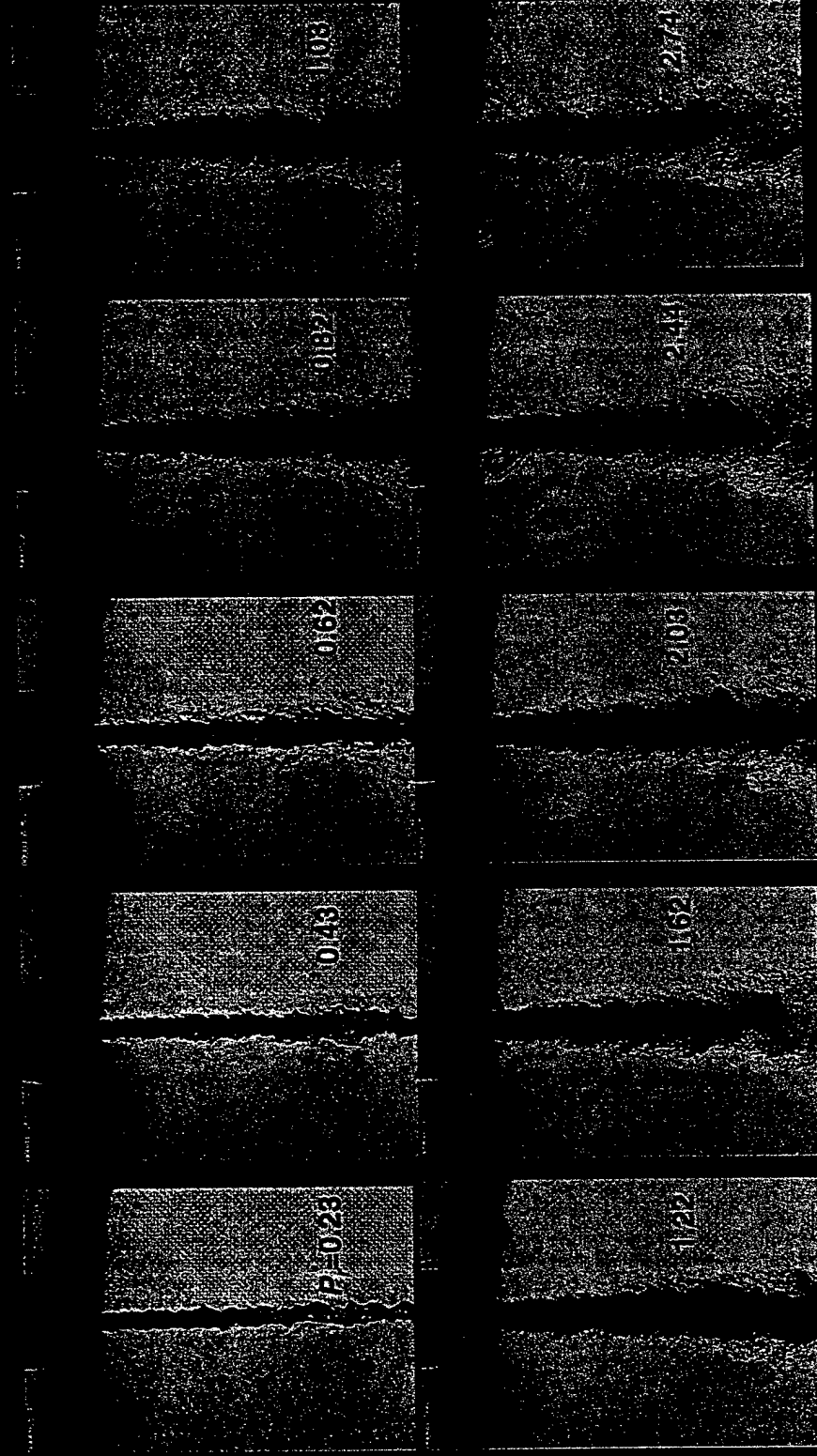
$T_{amb} = 300 \text{ K}$

$Re = 25,000 - 75,000$

$T_{cr} = 126 \text{ K}$

$T_{inj} = 99 - 120 \text{ K}$

$V_{inj} = 10 - 15 \text{ m/s}$



Mixing Layer Structure - N₂ into N₂

AFRL

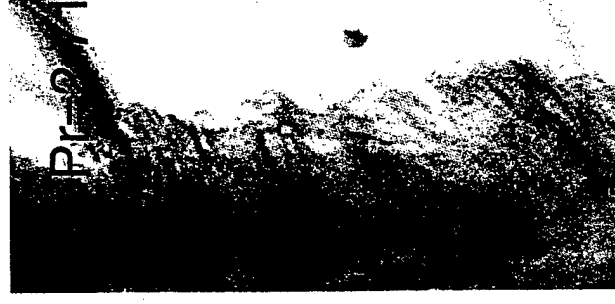
$P_{cr} = 3.39 \text{ Mpa}$, $T_{cr} = 126 \text{ K}$, $T_{inj} = 128 \text{ K}$, $T_{amb} = 300 \text{ K}$



Low Pres.
Subcritical
Droplets



Mod. Pres.
Supercritical
Transition

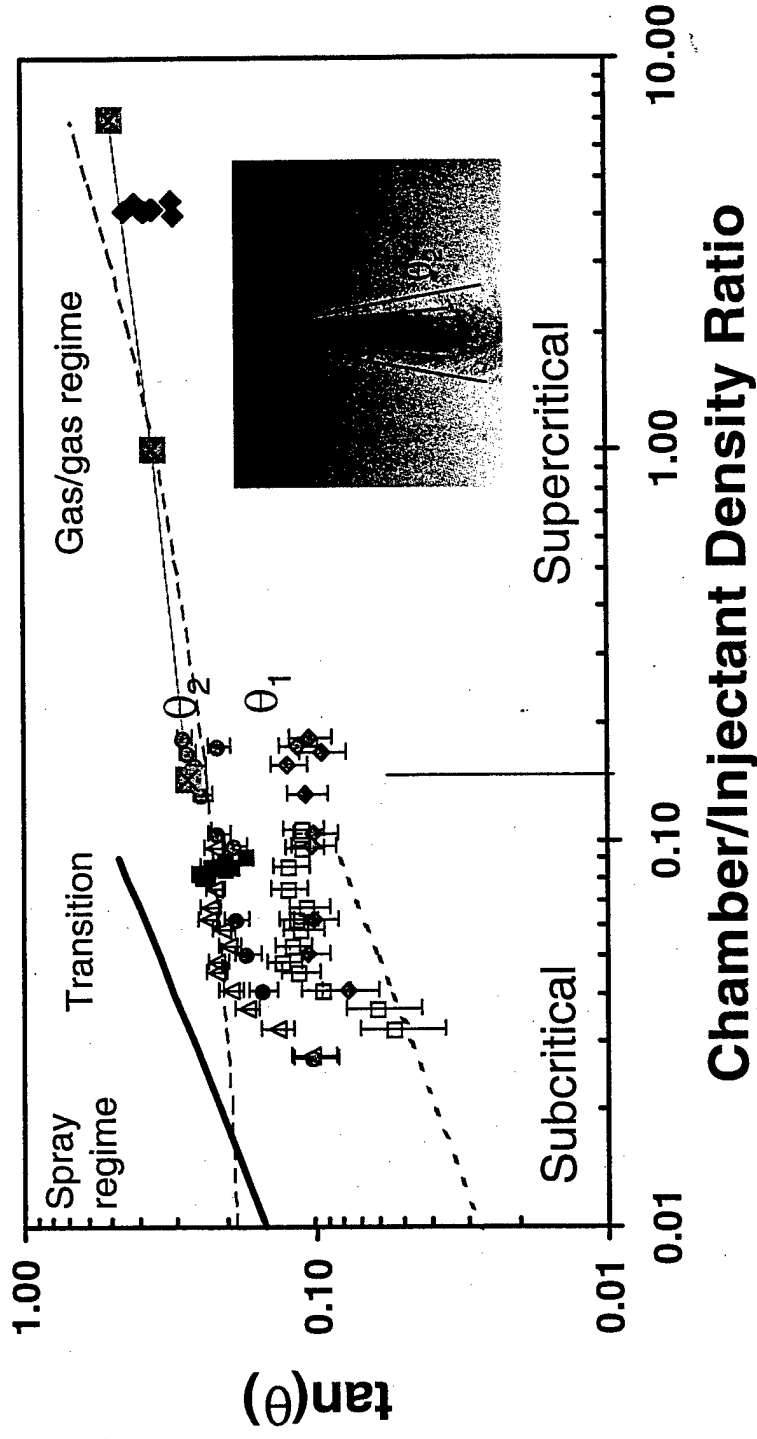
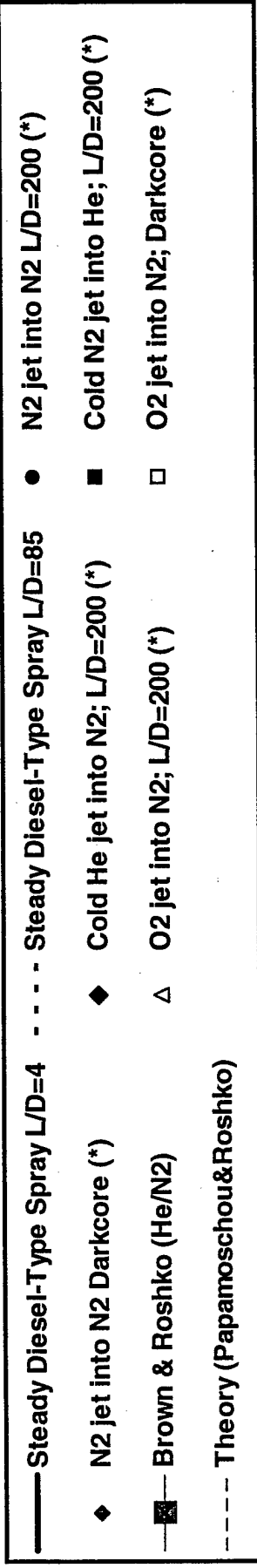


High Pres.
Supercritical
Gas layers

Jet Spreading Angles

AFRL

Chehrودي et. al., AIAA 99-0206, AIAA 99-2489



Characteristic Times

AFRL

- 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 equations for different cases

AFRL

- 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:

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

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

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

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

$$\theta_D \cong 0.212 [0.59 + (p_g/p_l)^{0.5}]$$

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

Empirical Correlation

AFRL

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

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

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 0.5 for supercritical gas-like jet. The transition point is found to be approximately when $(\tau_b / (\tau_b + \tau_g)) \cong 0.5$ (i.e. $\tau_b \cong \tau_g$).

Empirical Correlation (2)

AFRL

- $(\tau_b/(\tau_b + \tau_g))$ is assumed to be a dominant function of the density ratio (ρ_g/ρ_l) ; i.e. $\tau_b/(\tau_b + \tau_g) = F(\rho_g/\rho_l)$.
- The function F is only calculated for the N₂-into-N₂ case and is taken to be the same for other (N₂-into-He and N₂-into-Ar) cases. That is, for example, for N₂-into-He:

$$\theta_{ch} \cong 0.27 [G(\rho_g/\rho_l) + (\rho_g/\rho_l)^{0.5}] \quad \text{where}$$

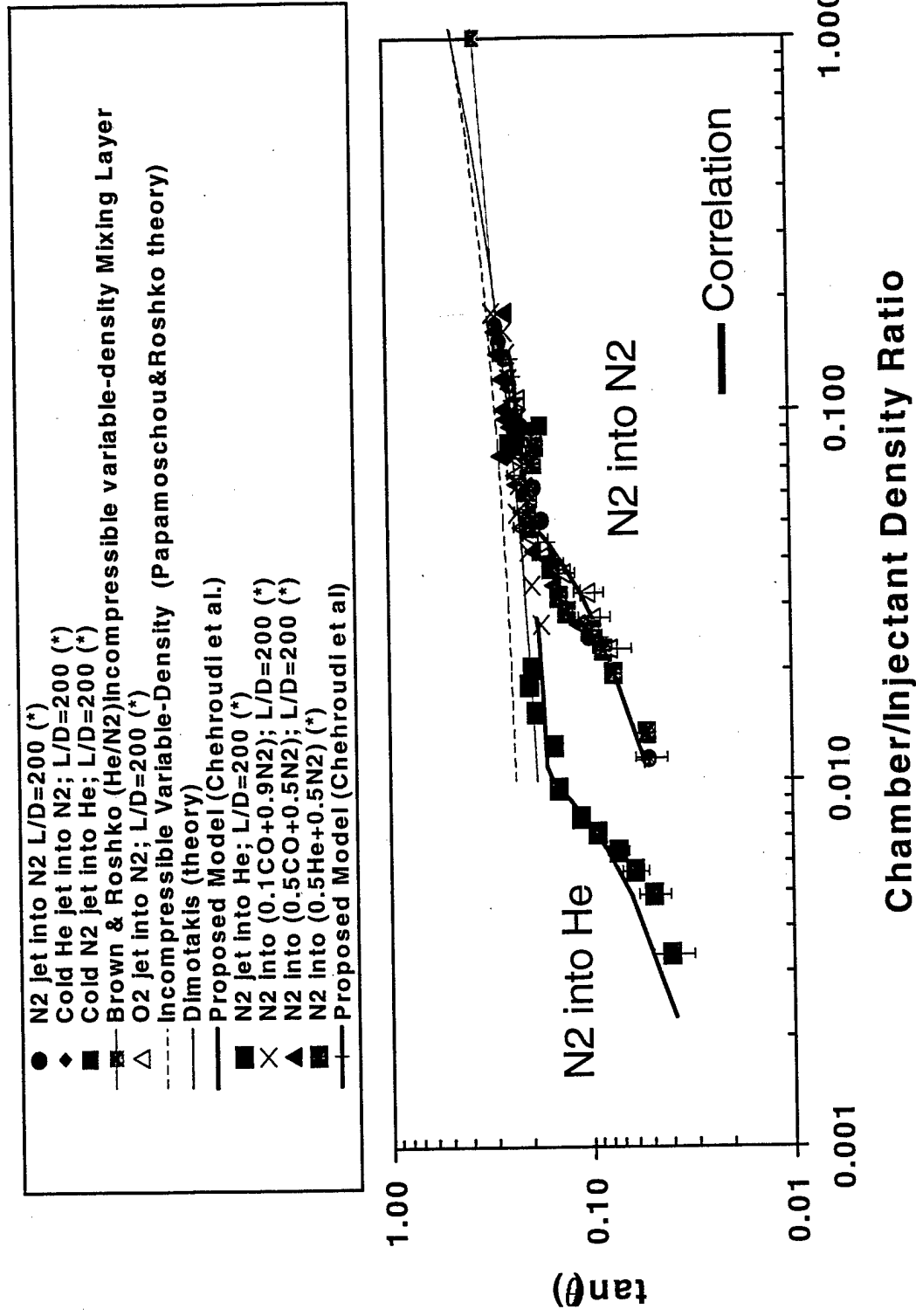
$$G(\rho_R) = F(\rho_R')$$

$$\rho_R = (\rho_g/\rho_l); \quad \rho_R' = \rho_R - (1-X)\rho_R = X\rho_R$$

X=1.0 for N₂-into-N₂; **X=0.2** for N₂-into-He; **X=1.2** for N₂-into-Ar.

Empirical Correlation (3)

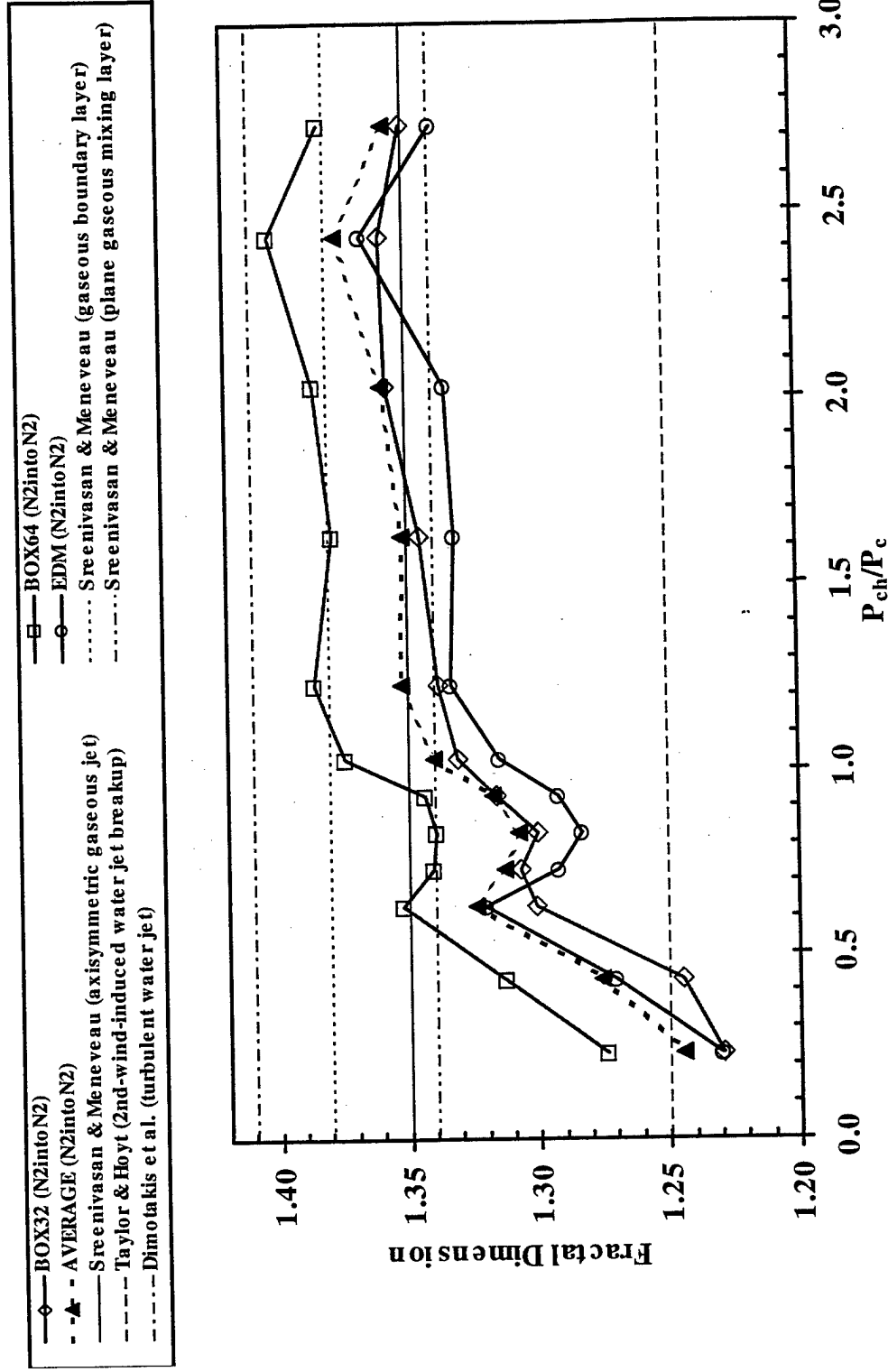
AFRL



Fractal Dimension vs Reduced Pressure

AFRL

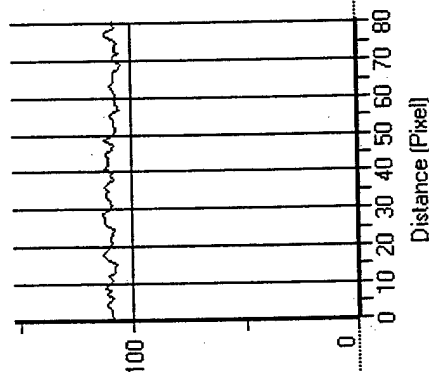
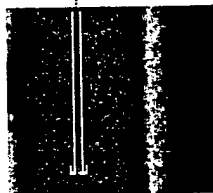
Chehrودي et. al., AIAA 99-2489



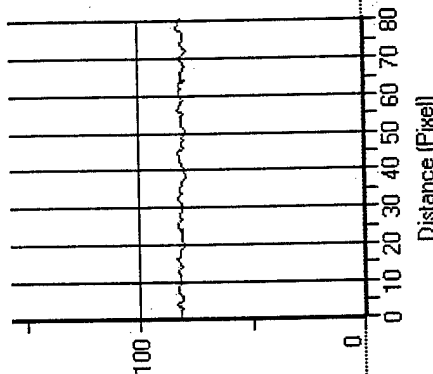
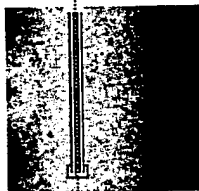
Results in Isothermal N₂ at 273 K

AFRL

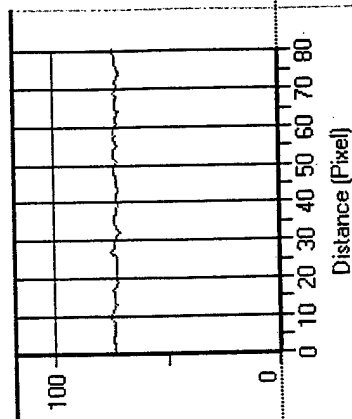
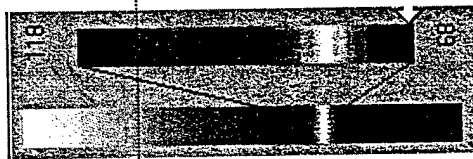
6.90 MPa (1000 psig)



2.82 MPa (400 psig)



1.46 MPa (200 psig)



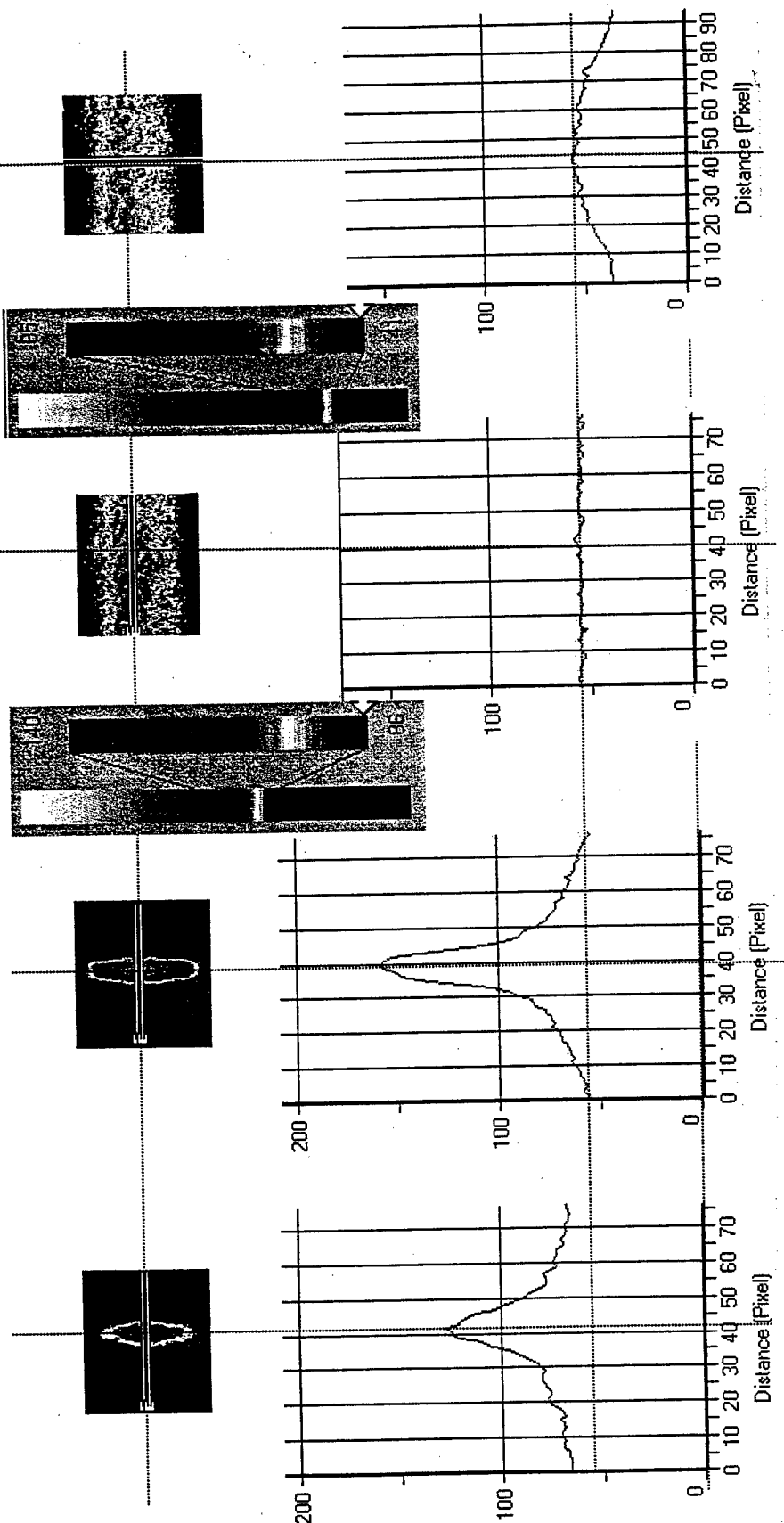
Chamber Pressure	Density Ratio Based on	Dark-background-corrected
Mpa	P-Measurement & Ideal Gas	Camera-measured
	Nitrogen	Intensity Ratio
		Nitrogen
6.90	4.73	4.78
2.82	1.93	1.89
1.46	1.00	1.00

2-D Raman Images, N₂ into N₂

AFRL

Re= 12,000 to 35,000; X/D = 2.44; sheet center

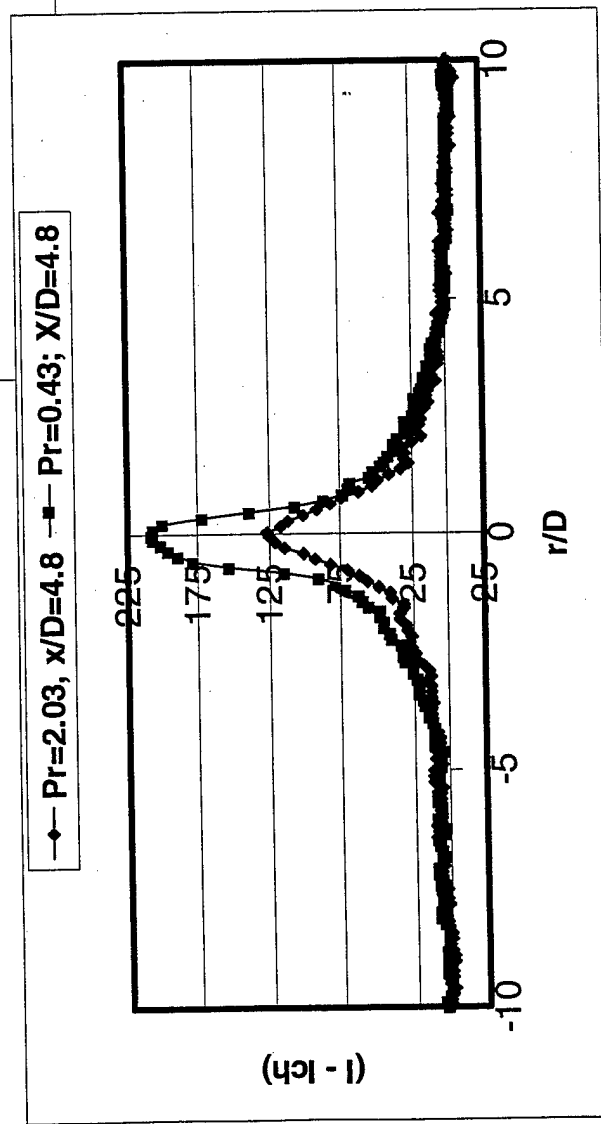
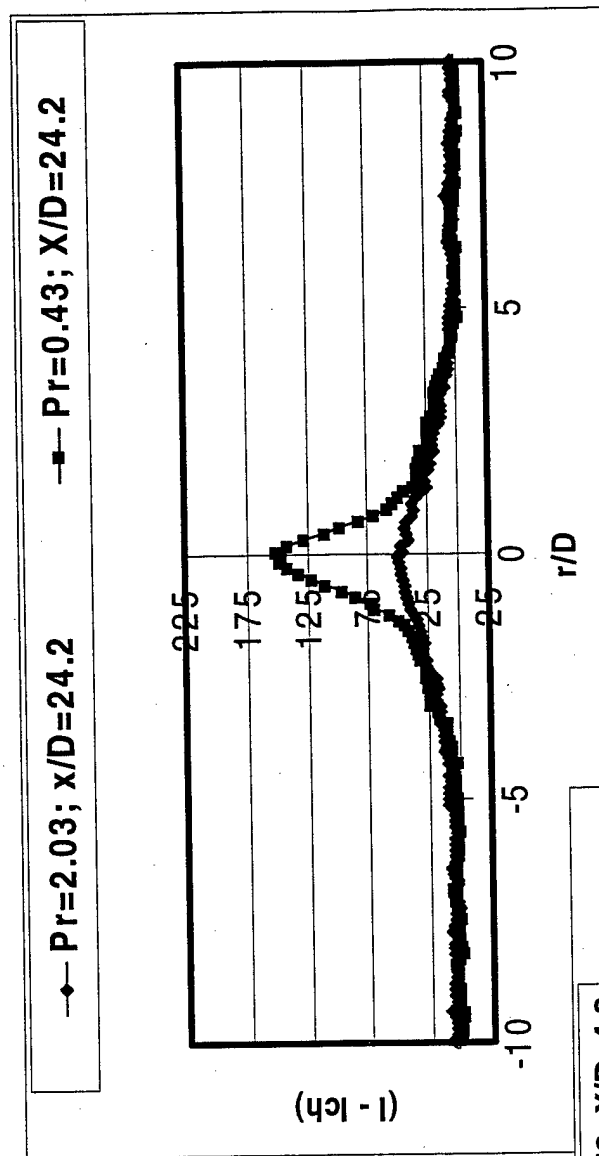
Supercritical Pr=2.03 Subcritical Pr=0.43 Laser Sheet Profile Pr=2.03



Intensity Defect vs Normalized Radius

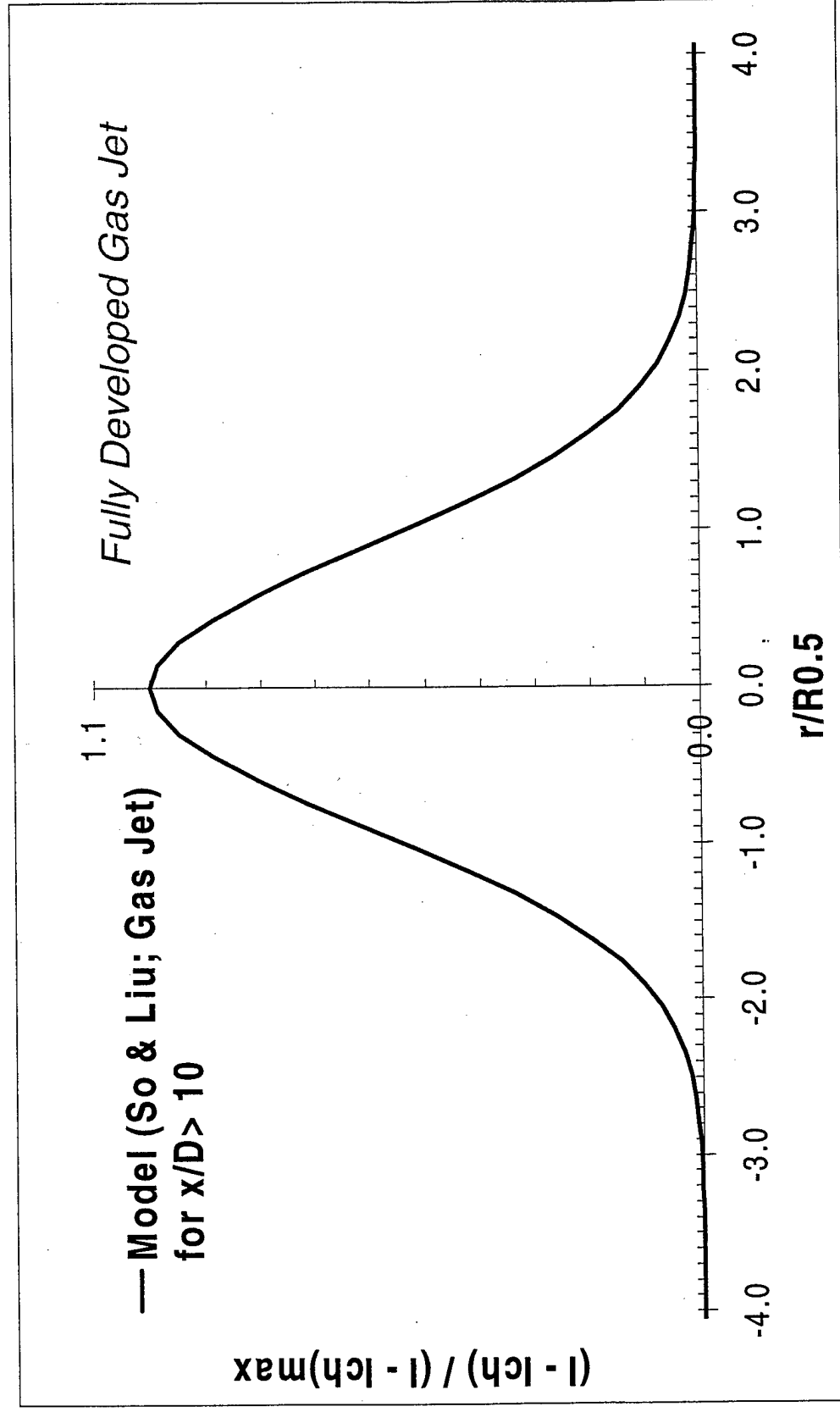
AFRL

N_2 into N_2



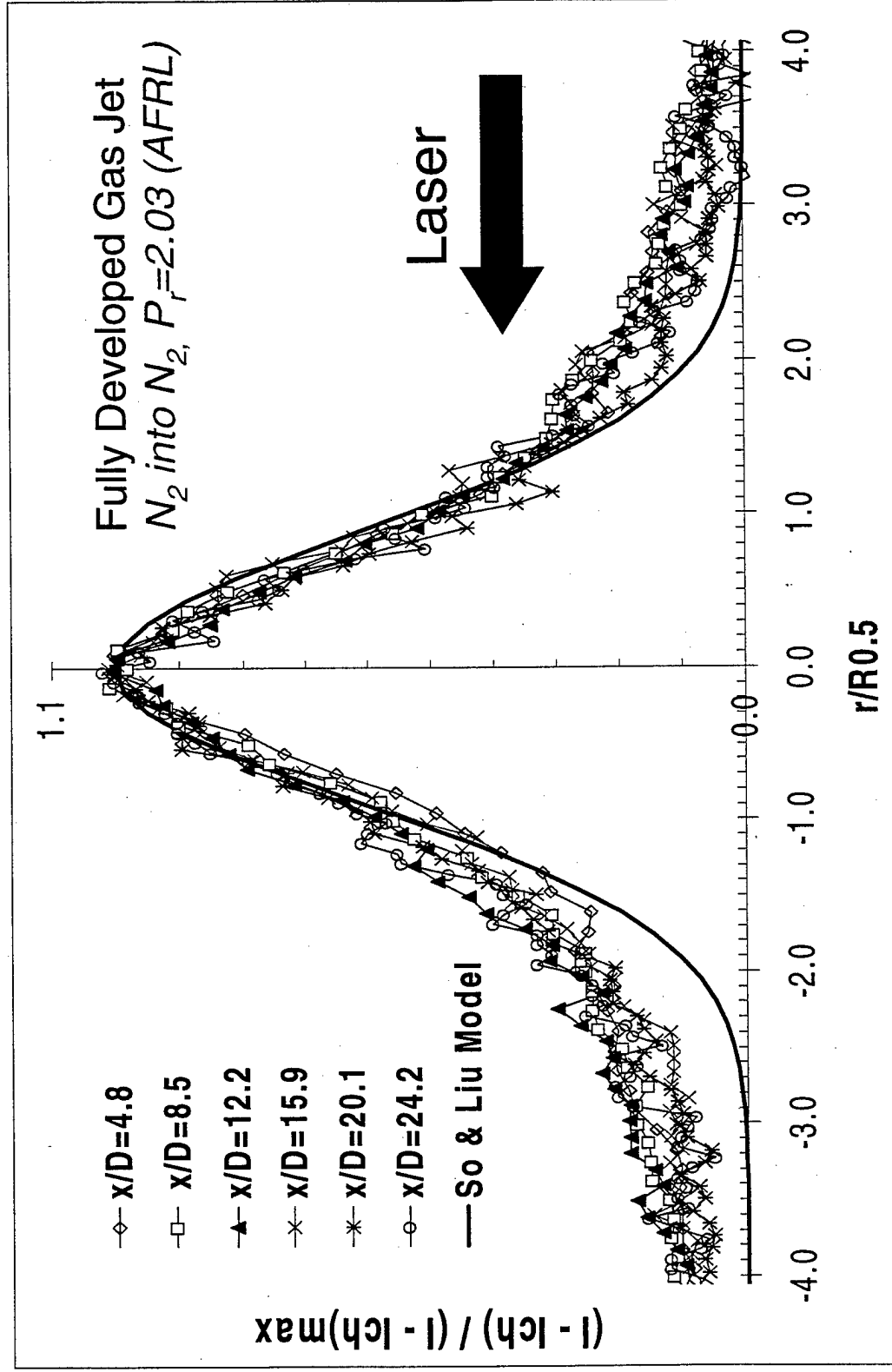
Normalized Intensity Defect Plot: Reference Case

AFRL



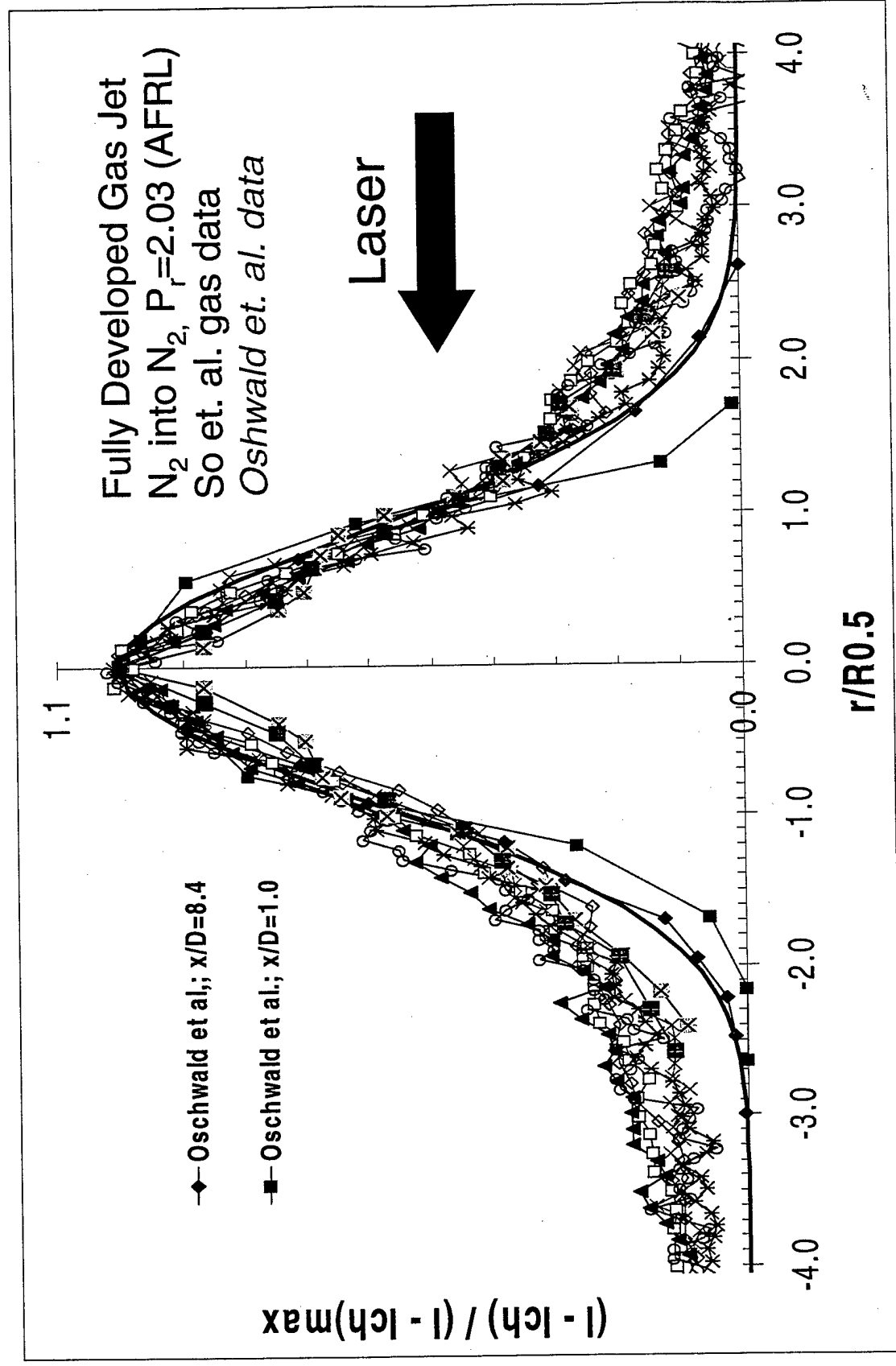
Normalized Intensity Defect Plot: Supercritical Regime

AFRL



Normalized Intensity Defect Plot: Supercritical Regime (3)

AFRL



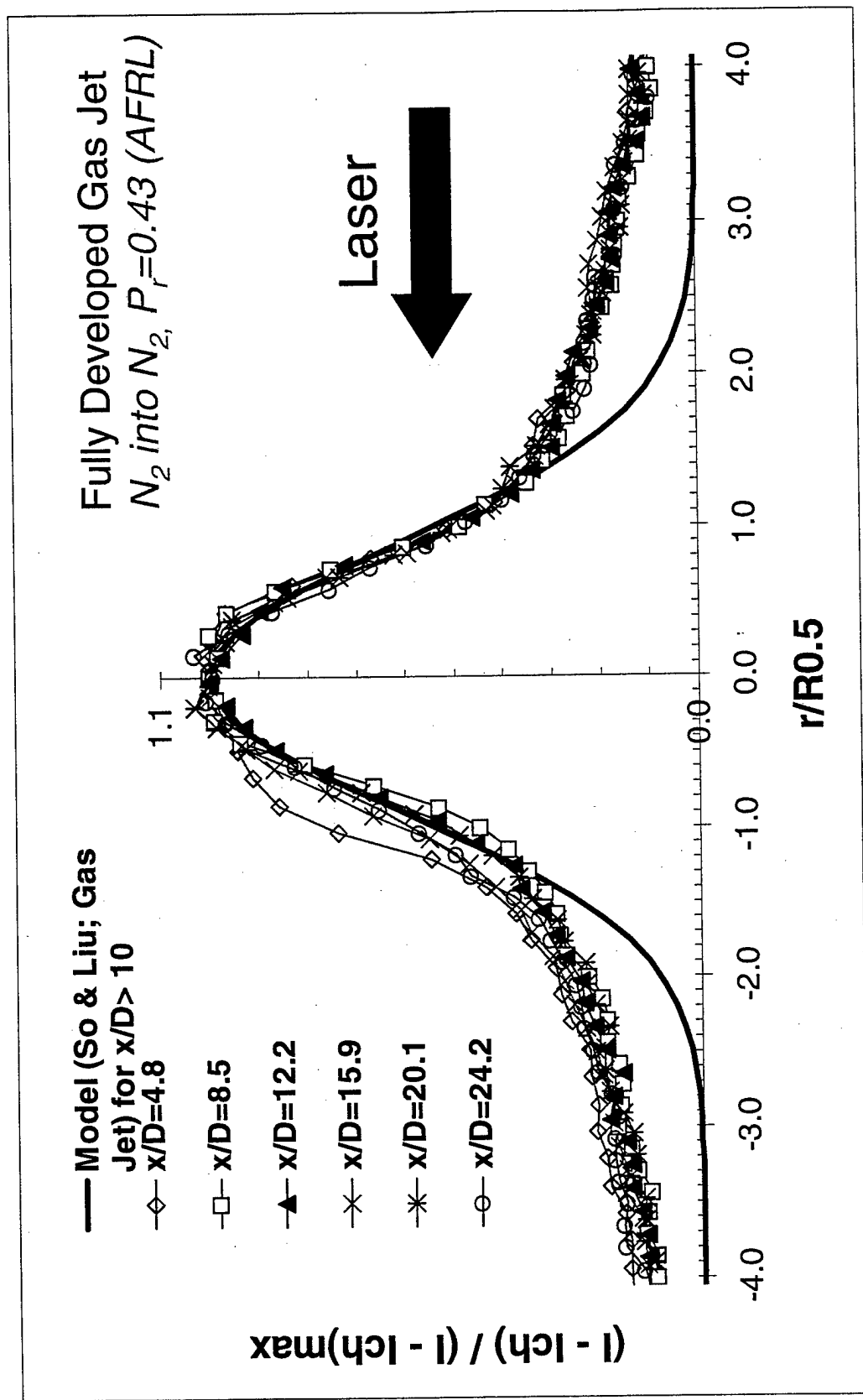
Normalized Intensity Defect Plot: Supercritical Regime (4)

AFRL

	X/D	Pch MPa	Pr	Inj. Temp K	Inj. Vel m/s	Re	Inj/Cham density ratio
Oschwald et al.	1.0	4.0	1.2	140	5.0	115000	3.3
Oschwald et al.	8.4	4.0	1.2	118	5.0	126000	12.5
Chehroudi et al.	4.8 to 24.4	6.9	2.0	95	8.0	35000	7.1
Chehroudi et al.	4.8 to 24.4	1.5	0.4	110	8.0	12000	40.6
So et. al.	5.1	0.1	--	275	11.6	5000	0.6
So et. al.	6.4	0.1	--	275	11.6	5000	0.6

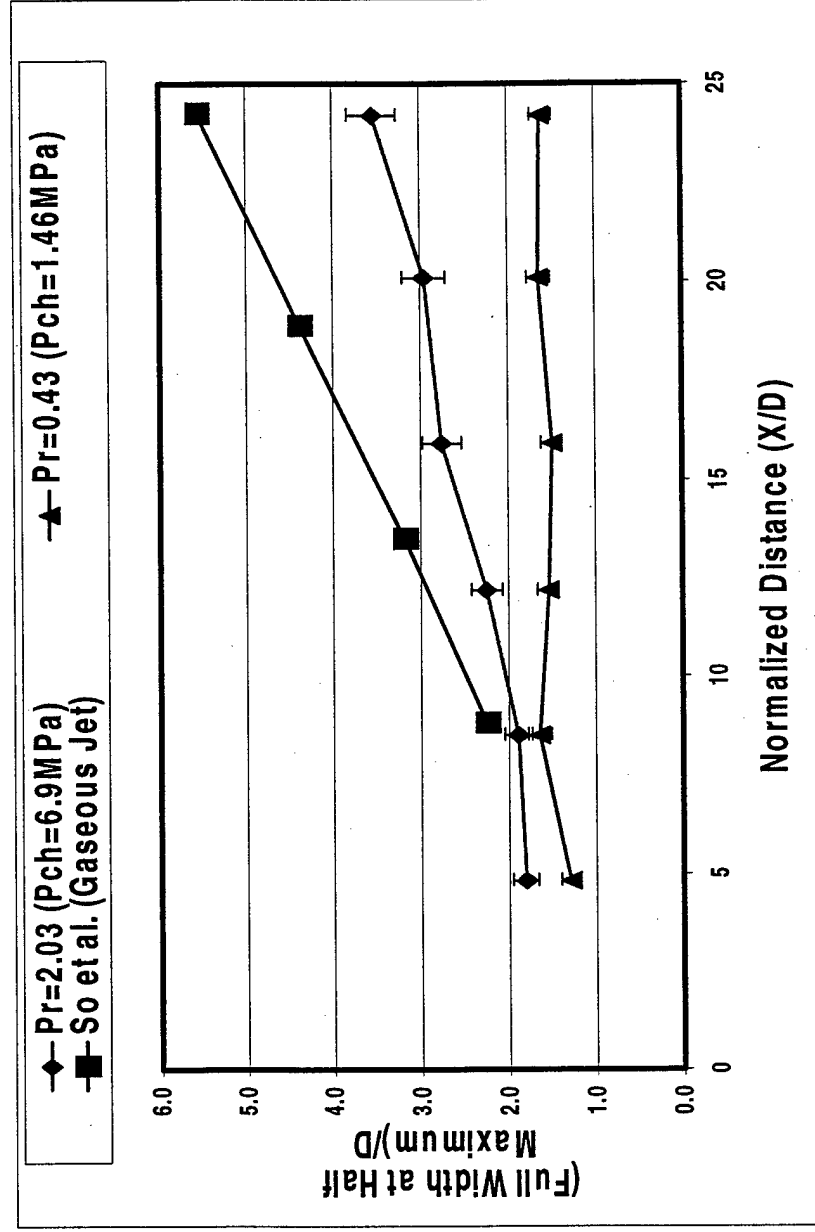
Normalized Intensity Defect Plot: Subcritical Regime

AFRL



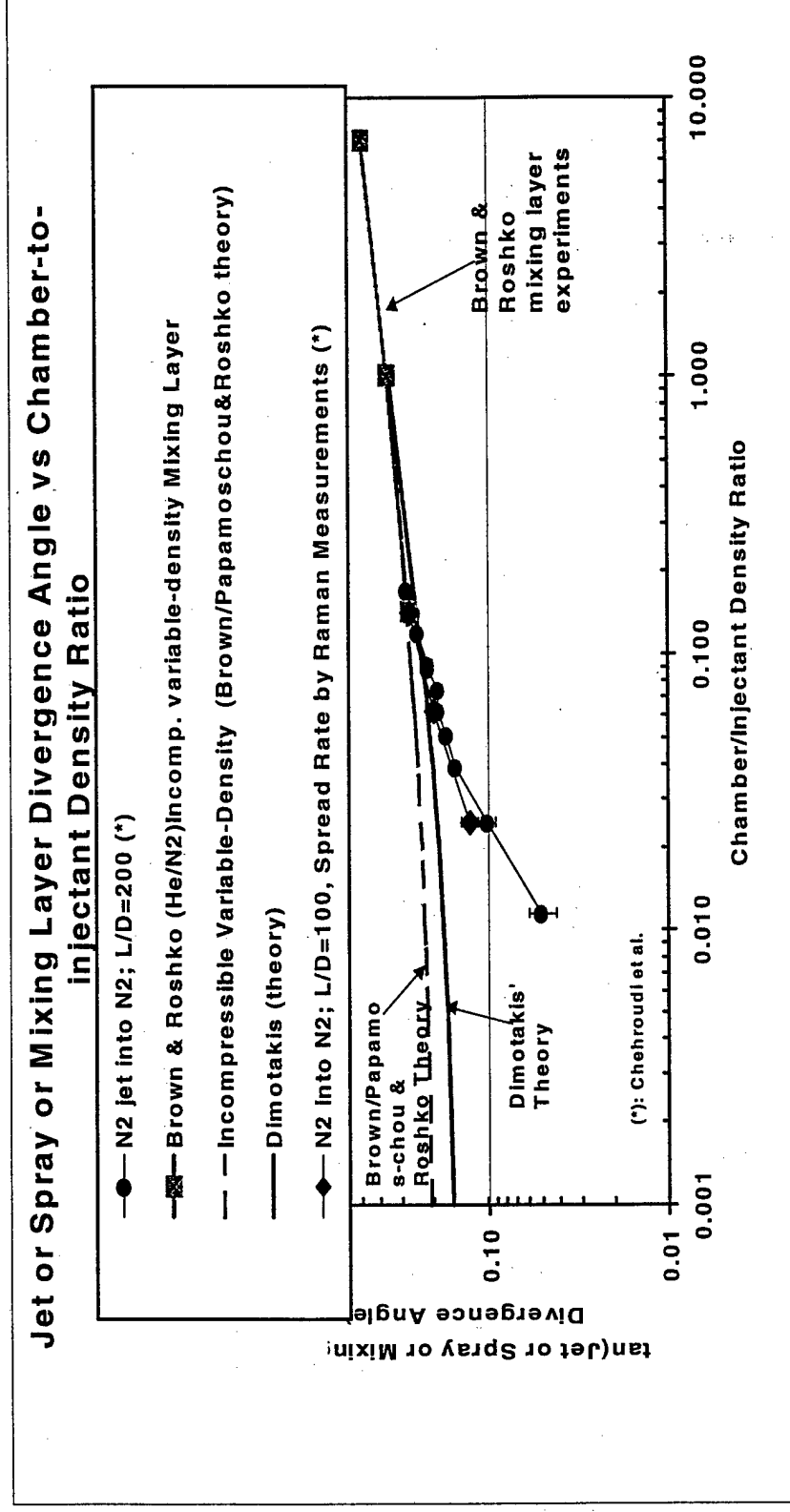
Growth Rates

AFRL



Comparison of Shadowgraph Measurements with Raman Measurements

AFRL



- Setting $\theta = 2 \times \text{FWHM}$ produces agreement with shadowgraph measurements.
 - Consistent with the observations of Brown and Roshko

Summary & Conclusions

AFRL

- Structural differences in cryogenic jets have been observed below and above the thermodynamic critical point.
- Liquid-Jet like appearance occurs up to near the critical point, similar to second wind-induced liquid jet breakup regime.
- Gas-jet like appearance occurs above the critical point. No drops are observed.
 - Supercritical spreading rate measurements agree quantitatively with incompressible variable density mixing layer experiments and theory.
 - Supercritical fractal dimensions agree quantitatively with gas jet measurements.
- New and existing mixing layer growth rate experiments and theory have for the first time been consolidated into a single plot as a function of density ratio, where the density ratio spans three orders of magnitude.
- A physical mechanism and correlation have been proposed to describe the transition from spray to gas jet behavior.

Summary & Conclusions (Raman)

A-FRL

- Measurement system integrity has been established by performing Raman measurements of isothermal N_2 at different pressures.
- Measurements were constrained to the near-field in order to maintain large Froude numbers (minimize buoyancy).
- Growth rates measured from Raman profiles measured at 2 x FWHM point agree well with shadowgraph measurements.
 - The equivalency of visual and density growth rates has also been reported in the literature (Brown & Roshko, 1974).
- To within experimental error, the near-field plots appear to reduce to self-similar shapes for both the supercritical and subcritical cases.
 - Not the same profile as for fully developed turbulent gas jets.
- The near-field supercritical profile more closely approaches that of fully developed turbulent gas jets than the near-field subcritical profile.

Future

AFRL

- Complete N₂-into-N₂ analysis.
- Reduce and analyze N₂-into-N₂/He data.
- Acoustic experiments.