Flowfield Characterization in a LOX/GH_2 Propellant Rocket

S. Pal, M. D. Moser, H. M. Ryan, M. J. Foust and R. J. Santoro

Propulsion Engineering Research Center
and
Department of Mechanical Engineering
The Pennsylvania State University
University Park, PA 16802

Statement of Problem

There is a critical shortage of data pertaining to the flowfield characteristics in a liquid propellant rocket chamber for hot-fire conditions. For a liquid oxygen (LOX)/gaseous hydrogen (GH_2) propellant combination, either shear or swirl coaxial injectors are typically used to atomize the liquid propellant into drops. Understanding the atomization process under hot-fire conditions represents the first step in understanding the subsequent processes of vaporization, mixing and combustion. The flowfield here is two-phase and therefore experiments that detail the intact liquid jet, drop size and velocity, and combustion length are necessary for understanding the physics of the problem.

Objective of Work

The objective of the current work is to experimentally characterize the flowfield associated with an uni-element shear coaxial injector burning LOX/GH_2 propellants. These experiments were carried out in an optically-accessible rocket chamber operating at a high pressure ($\approx$400 psia). Quantitative measurements of drop size and velocity were obtained along with qualitative measurements of the disintegrating jet.

Approach

The experiments were conducted at the Cryogenic Combustion Laboratory at Penn State University. This laboratory provides the capability for firing both gaseous and liquid propellant sub-scale rocket engines. A modular rocket chamber which provides extensive optical access was designed for the experiments. The cross-section of the rocket is 50.8 mm (2 in.) square and the chamber length which can be easily varied was 248 mm (9.75 in.). The flowfield downstream of a shear coaxial injector was characterized using laser-based diagnostic techniques. The inner diameter of the LOX post was 3.43 mm (0.135 in.) and the post was recessed 3.78 mm (0.15 in.). The inner diameter of the fuel annulus was 4.19 mm (0.165 in.) and the outer diameter was 7.11 mm (0.28 in.). The nominal LOX and GH_2 flowrates were 0.11 kg/s (0.25 lbm/s) and 0.021 kg/s (0.047 lbm/s) respectively, thus resulting in a nominal O/F ratio of 5.3:1. These flow rates, coupled with the nozzle dimensions yielded a chamber pressure of 2.74 MPa ($\approx$400 psia). The duration of a test run was four seconds.

A Phase Doppler Particle Analyzer (PDPA) was used to measure LOX drop size and velocity at various radial locations for an axial position 63.5 mm (2.5 in.) downstream of the injector face. The measured Sauter Mean diameter (SMD) ranged from 110 μm at the centerline to about 60 μm at a 9.5 mm (0.375 in.) radial location. At greater radial locations, no drops were observed. The results indicate that under hot-fire conditions, the drops formed from the shear coaxial injector are confined to a narrow circumferential region.

Conclusions

These experiments represent the first time that drop sizes have been measured under combusting conditions for cryogenic propellants. These results are, in general, encouraging with respect to applications of laser-based diagnostics to LOX/GH_2 uni-element rocket studies. A comprehensive mapping of the flowfield will need to be completed to gain a thorough understanding of the physics of this complex problem.

Flowfield Characterization in a Liquid Oxygen/Gaseous Hydrogen Propellant Rocket

S. Pal, M. D. Moser, H. M. Ryan, M. J. Foust and R. J. Santoro

The Propulsion Engineering Research Center
The Pennsylvania State University
University Park, PA 16802

11th Workshop for CFD Applications in Rocket Propulsion

April 20-22, 1993

NASA Marshall Space Flight Center
Huntsville, Alabama

PRESENTATION OUTLINE

Motivation

Background

Objective

Experimental

- **Facility**
- **Rocket chamber**
- **Diagnostics**

Results

Summary

MOTIVATION

To obtain fundamental data under well characterized conditions

- **For gaseous propellant rockets**
- **For liquid propellant rockets**
- **For various injector types**

Fundamental data would form the basis for

- **Empirical correlation validation**
- **CFD code validation**

BACKGROUND

Atomization models typically are:

- Anchored to cold flow experimental results

  We and *Re* of cold flow experiments differ by an order of magnitude from actual rocket conditions

  Results have to be extrapolated

- Predicted from analytical models based on linear stability theory

Drop size data for hot-fire conditions would:

- Validate atomization models

- Validate methodology for extending cold flow data to hot flow conditions

- Develop hot-flow correlations for direct use in combustion models

OBJECTIVE

To characterize the flowfield downstream of a shear coaxial injector using LOX/GH_2 propellants under combusting conditions

- **Drop size and velocity measurements using Phase Doppler Interferometry**

- **Laser sheet visualizations of near breakup region**

FACILITY CAPABILITIES

Propulsion Engineering Research Center
Cryogenic Combustion Laboratory

Propellants:

- Gaseous Hydrogen
- Gaseous Methane
- Gaseous Oxygen
- Liquid Oxygen

Flow rates (maximum):

Gaseous oxygen:	0.1 lbm/s
Liquid oxygen:	1.0 lbm/s
Gaseous hydrogen:	0.25 lbm/s

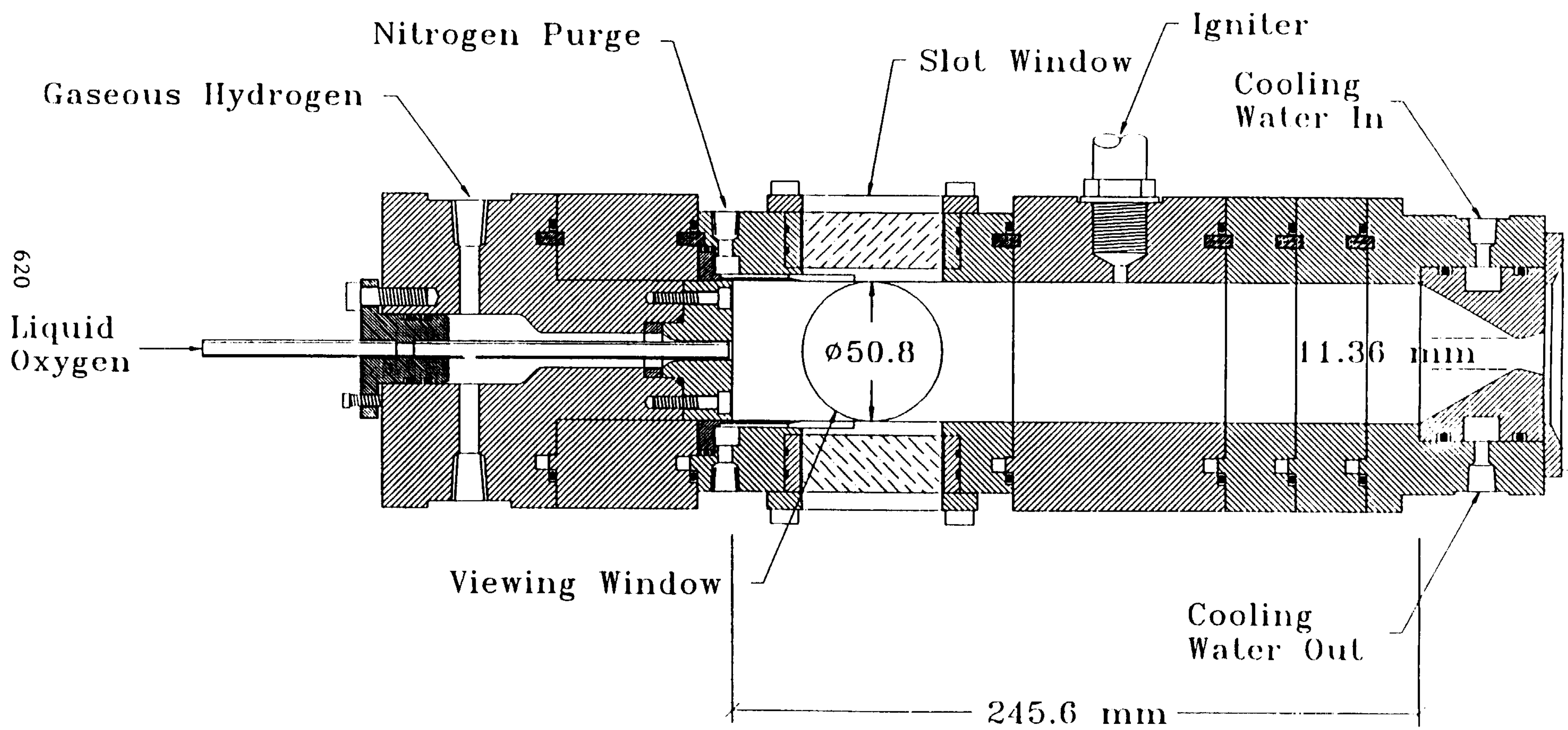
Typical mixture ratios: 4 - 8

Maximum chamber operating pressure: 1000 psi

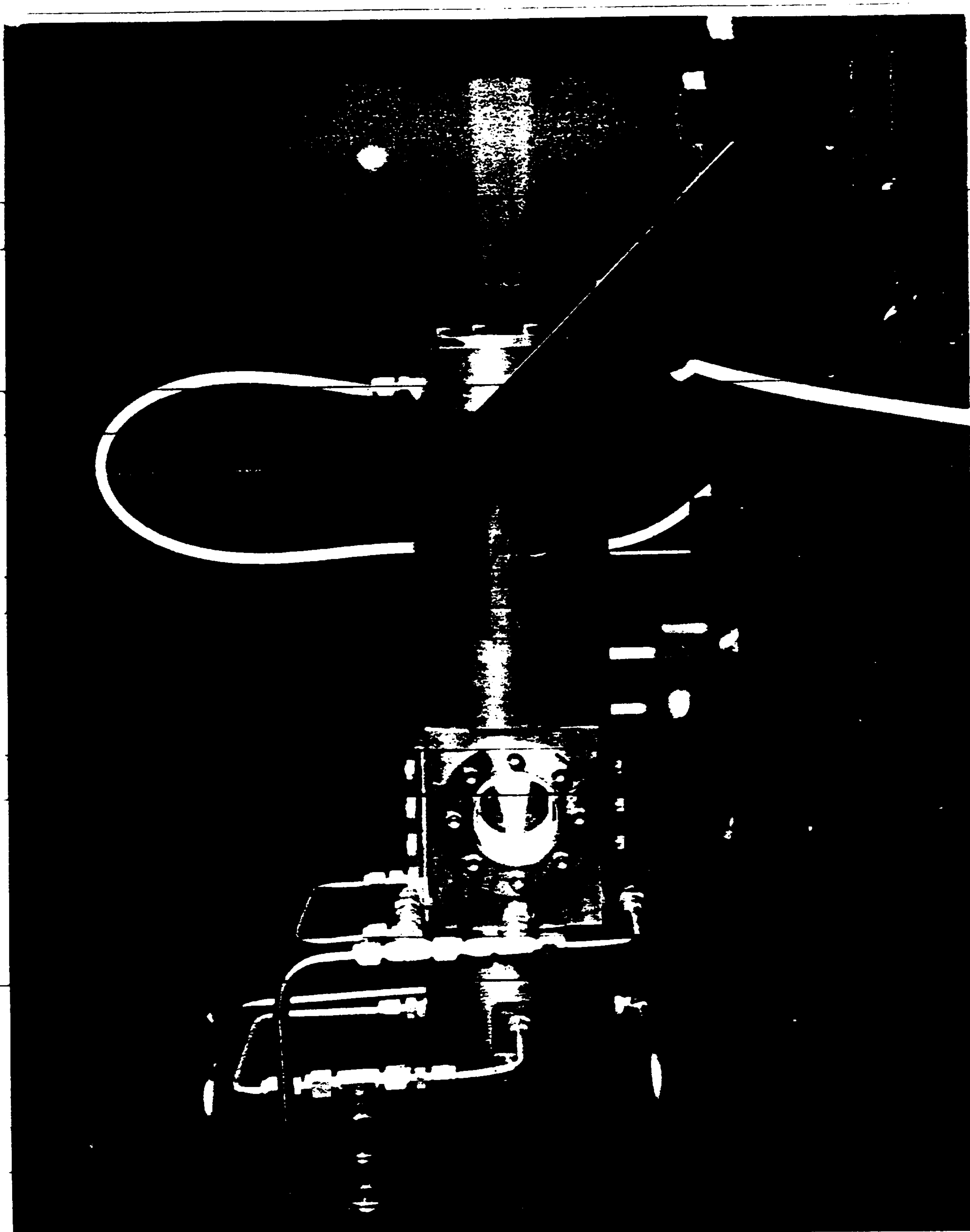
Typical test time: 1 - 5 s

Longer tests subject to hardware cooling and gas supply specifications

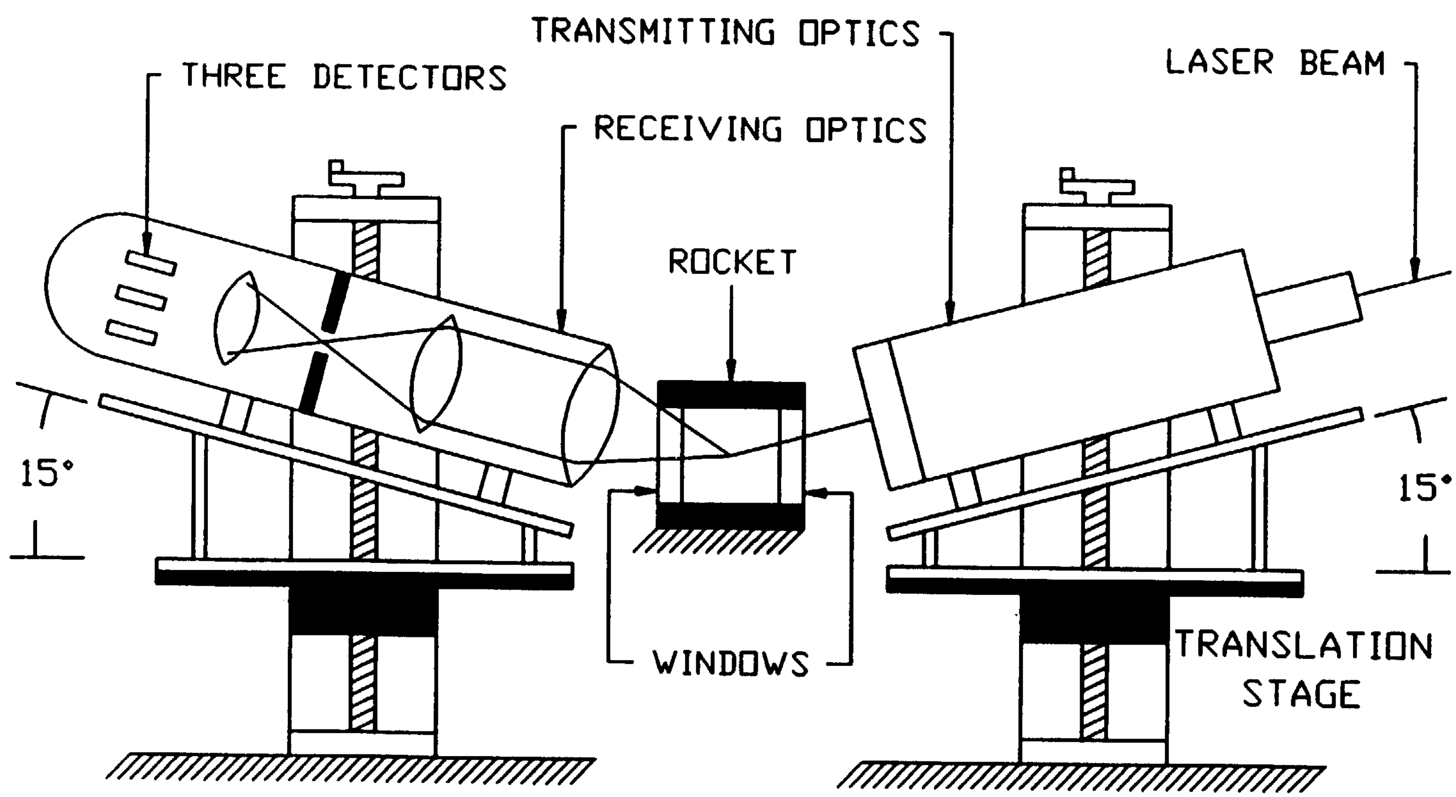
PENN STATE ROCKET



Cross-Sectional View of the Windowed Rocket Chamber



EXPERIMENTAL SCHEMATIC



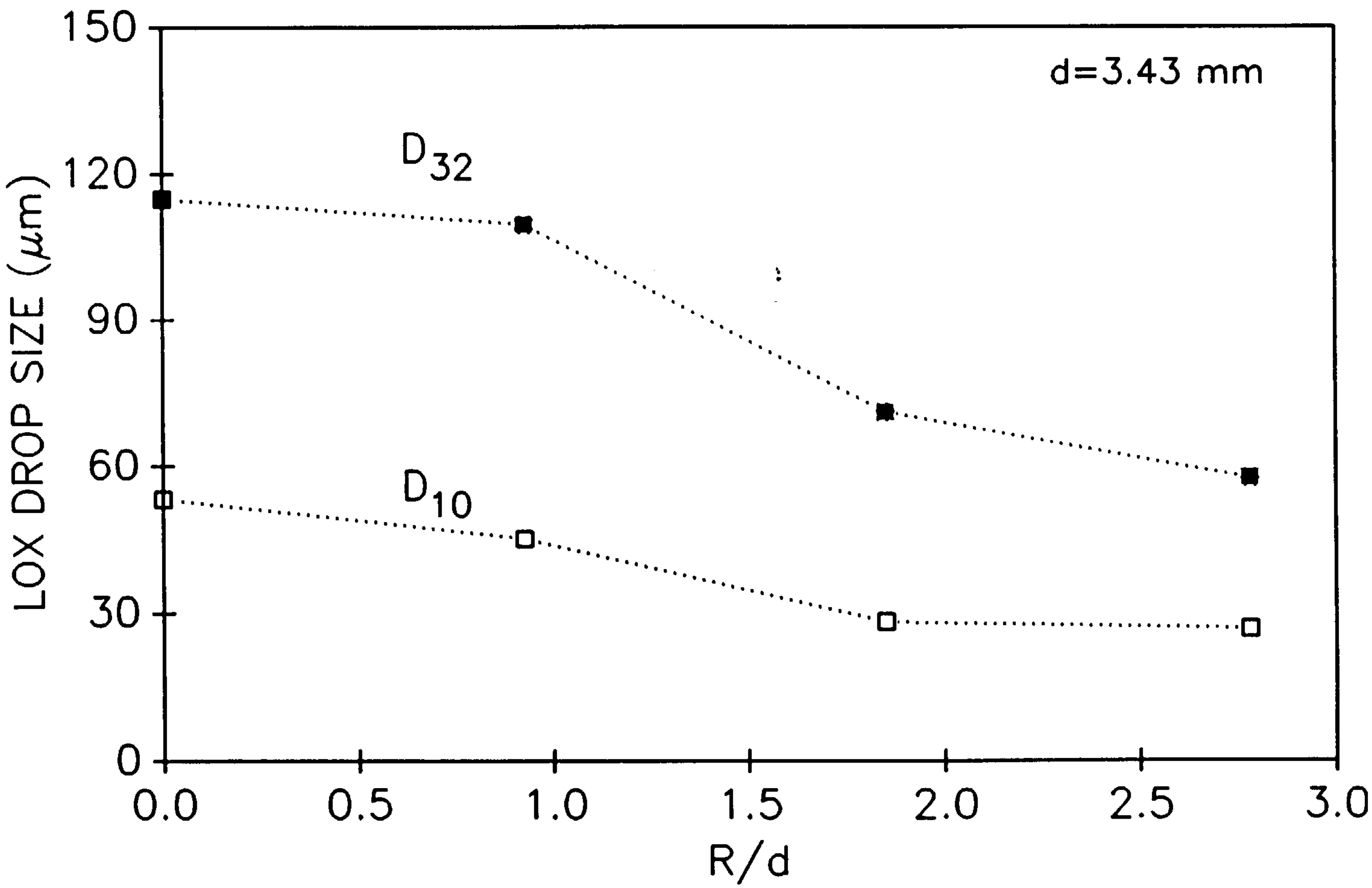
THIS PAGE LEFT BLANK INTENTIONALLY

TEST CONDITIONS

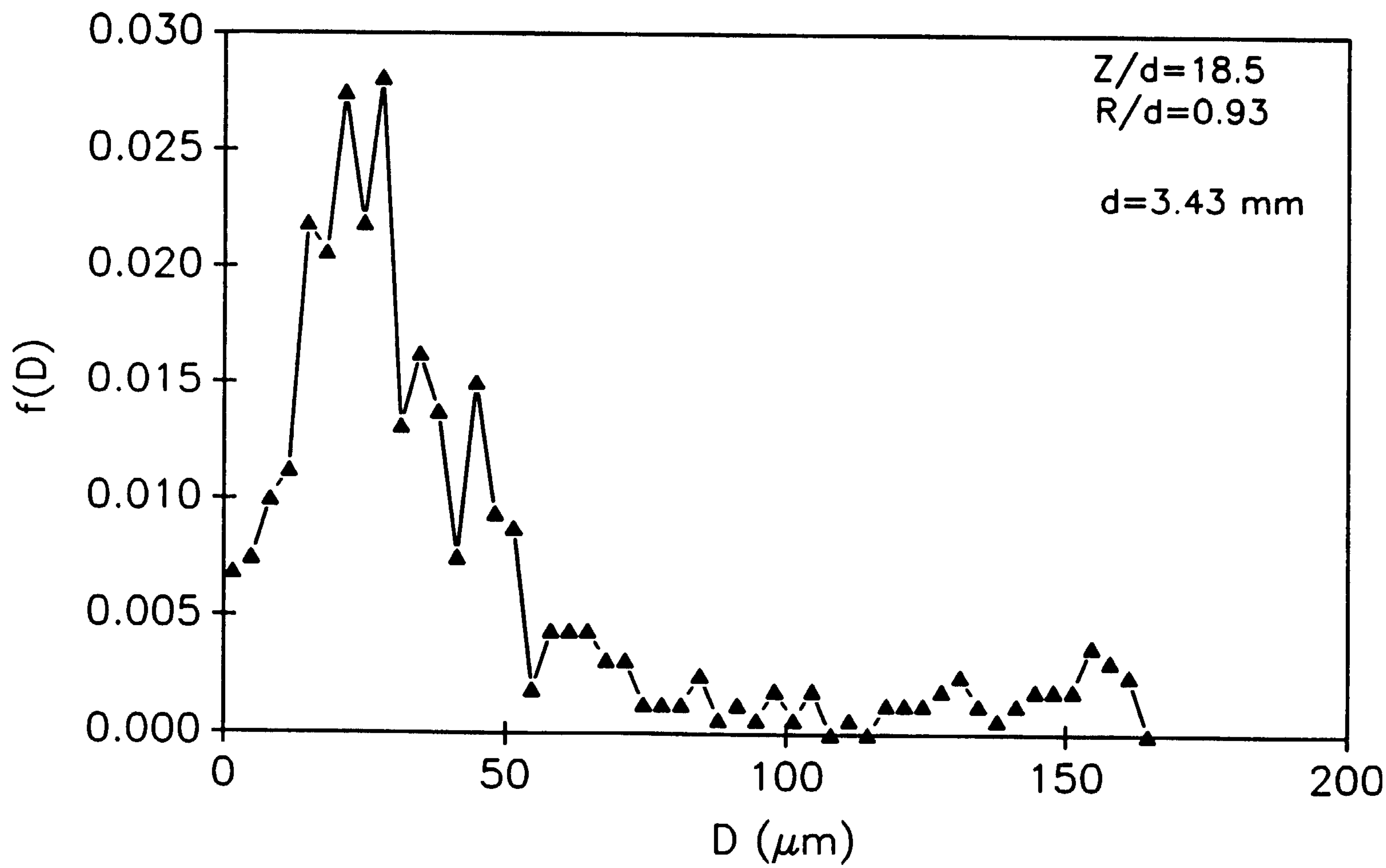
Chamber pressure	2.67 Mpa (387 psia)
LOX flowrate	0.112 kg/s (0.245 lbm/s)
GH_2 flowrate	0.021 kg/s (0.045 lbm/s)
Mixture ratio (O/F)	5.4
LOX velocity	13.5 m/s (44.1 ft/s)
GH_2 velocity	381 m/s (1250 ft/s)
Momentum ratio (F/O)	5.22
Velocity ratio (F/O)	28.3
Re[1]	5.03×10^5
We[2]	2.06×10^5

[1] $Re = \rho_l U_l \, d / \mu_l$
[2] $We = \rho_g (U_g - U_l)^2 d / \sigma$

MEAN DROP DIAMETER VS. RADIAL LOCATION
Z=63.5 mm (Z/d=18.5)

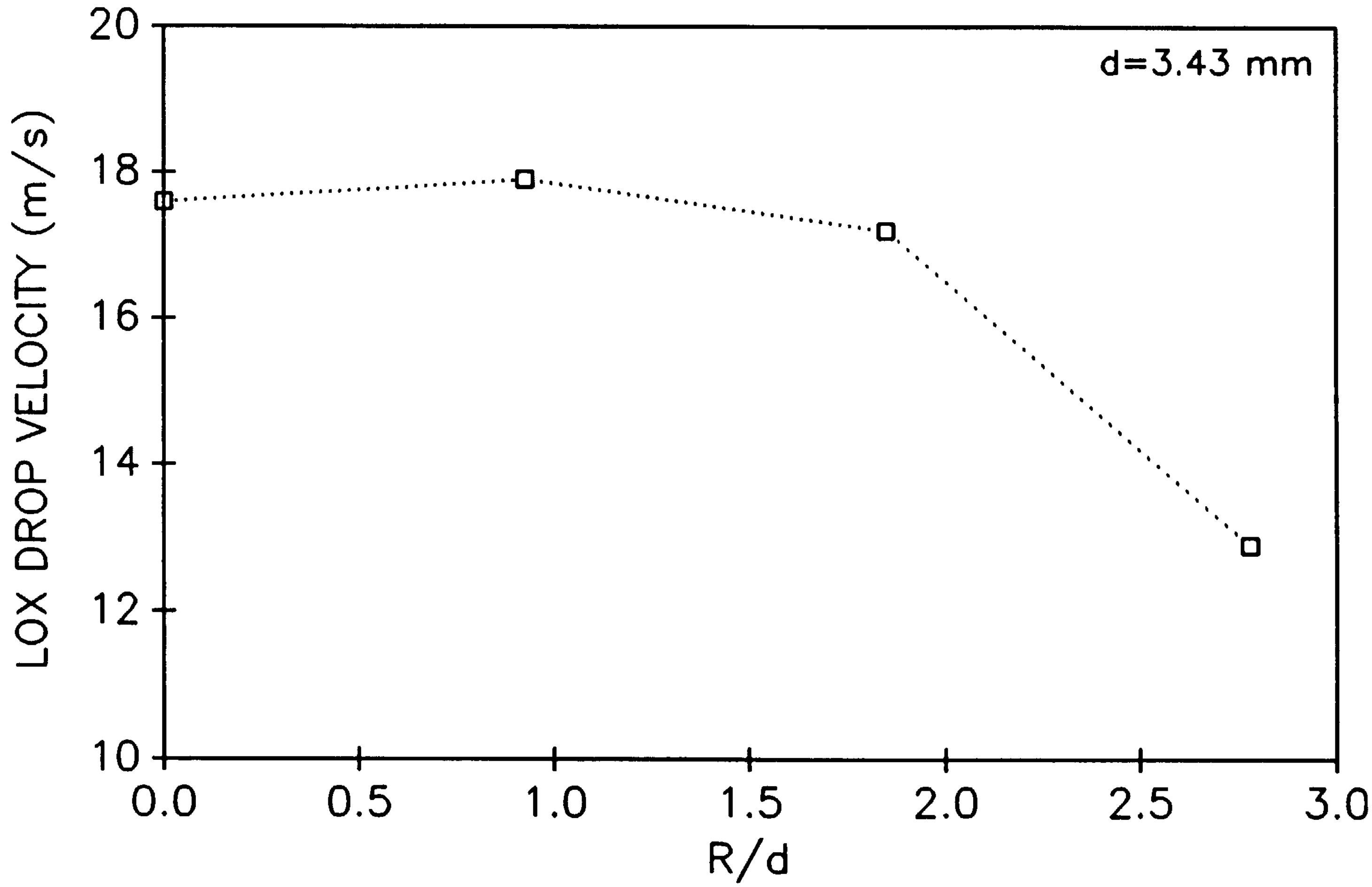


LOX DROP SIZE DISTRIBUTION



MEAN DROP VELOCITY VS. RADIAL LOCATION

Z=63.5 mm (Z/d=18.5)



ROCKET PARAMETERS

Run	Chamber Pressure (MPa)/ (psia)	LOX Flowrate (kg/s)/ (lbm/s)	GH_2 Flowrate (kg/s)/ (lbm/s)	Mixture Ratio (O/F)	Momentum Ratio (F/O)	Velocity Ratio (F/O)	Re_l[1] ($x10^5$)	We_g[2] ($x10^5$)
1	2.79/404	0.120/ 0.264	0.021/ 0.047	5.6	4.70	26.8	4.97	1.61
2	2.72/395	0.110/ 0.243	0.021/ 0.047	5.2	5.58	29.2	5.11	1.95
3	2.73/396	0.113/ 0.250	0.021/ 0.047	5.3	5.19	27.9	5.25	2.07
4	2.43/352	0.103/ 0.227	0.019/ 0.041	5.5	5.41	29.3	4.80	2.59

[1] $Re_l = \rho_l U_l d / \mu_l$

[2] $We_g = \rho_g (U_g - U_l)^2 d / \sigma$

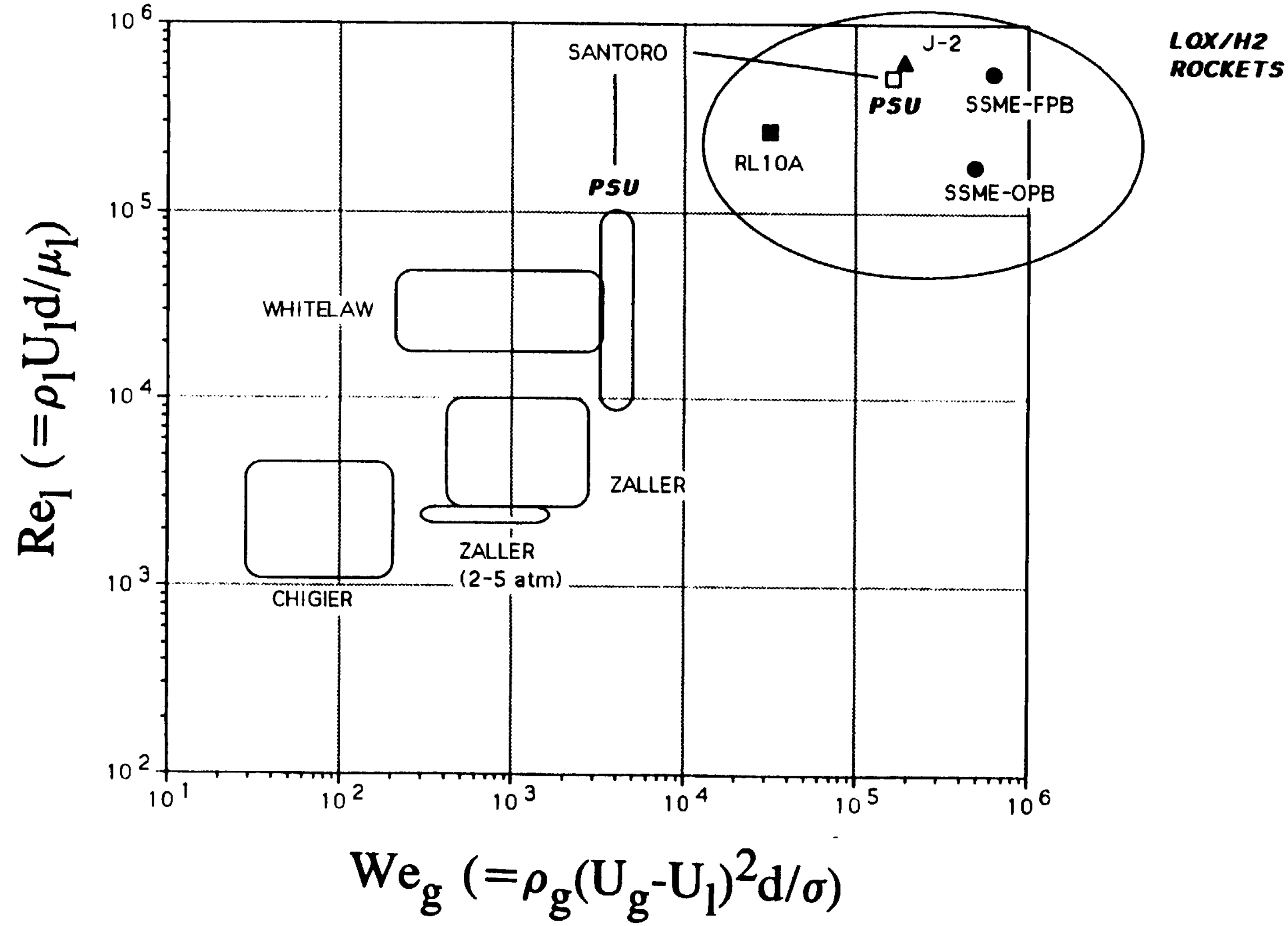
PDPA RESULTS

Axial Location, Z=63.5 mm (Z/d=18.5)
LOX Post I.D., d=3.43 mm

Run	R/d	D_{10} (μm)	D_{32} (μm)	V (m/s)	# Drops	% Val.	Run Time (sec.)
1	0.00	53.2	114.9	17.6	149	16%	1.41
2	0.93	45.1	109.7	17.9	484	21%	1.03
3	1.85	28.2	71.0	17.2	448	46%	1.52
4	2.78	26.8	57.5	12.9	45	62%	0.82

SHEAR-COAXIAL INJECTOR SPRAYS

Re_l vs. We_g



DROP SIZE EQUATIONS

NUKIYAMA/TANASAWA (1930) - *E*

$$\overline{D}_{32} = \frac{585}{V_r}\sqrt{\frac{\sigma}{\rho_l}} + 597\left(\frac{\mu_l}{\sqrt{\sigma\rho_l}}\right)^{0.45}\left(1000\frac{\dot{m}_l}{\rho_l}\frac{\rho_g}{\dot{m}_g}\right)^{1.5}$$

WEISS/WORSHAM (1959) - *SI

$$\overline{D}_{V0.5} = 0.61\left(1 + 1000\frac{\rho_g}{\rho_l}\right)\left(\frac{V_r\mu_l}{\sigma}\right)^{\frac{1}{6}}\left(\frac{\sigma}{\rho_g V_r^2}\right)\left(\frac{\rho_l\sigma\mu_g}{\mu_l^4}\left(\dot{m}_l + \dot{m}_g\right)\right)^{\frac{1}{12}}$$

MAYER (1961) - *SI

$$\overline{D}_{V0.5} = 9\pi\sqrt[3]{16}B\left(\frac{\mu_l\sqrt{\sigma}}{\rho_g V_g^2\sqrt{\rho_l}}\right)^{\frac{1}{3}}$$

LORENZETTO/LEFEBVRE (1977) - *SI

$$\overline{D}_{32} = 0.95\left(\frac{\sigma^{0.33}m_l^{0.33}}{V_r\rho_l^{0.37}\rho_g^{0.3}}\right)\left(1 + \frac{\dot{m}_l}{\dot{m}_g}\right)^{1.7} + 0.13\mu_l\left(\frac{d}{\sigma\rho_l}\right)^{0.5}\left(1 + \frac{\dot{m}_l}{\dot{m}_g}\right)^{1.7}$$

ZALLER (1993) - *SI

$$\overline{D}_{30} = 3.62\left(\frac{\mu_g^{1.5}}{\rho_g\sigma^{1.5}}\right)\left(\frac{\dot{m}_l}{\dot{m}_g}\right)^{0.4}\frac{1}{V_r^{0.5}}$$

E	*English Units*	* *Dimensionally Correct*
SI	*Metric Units*	

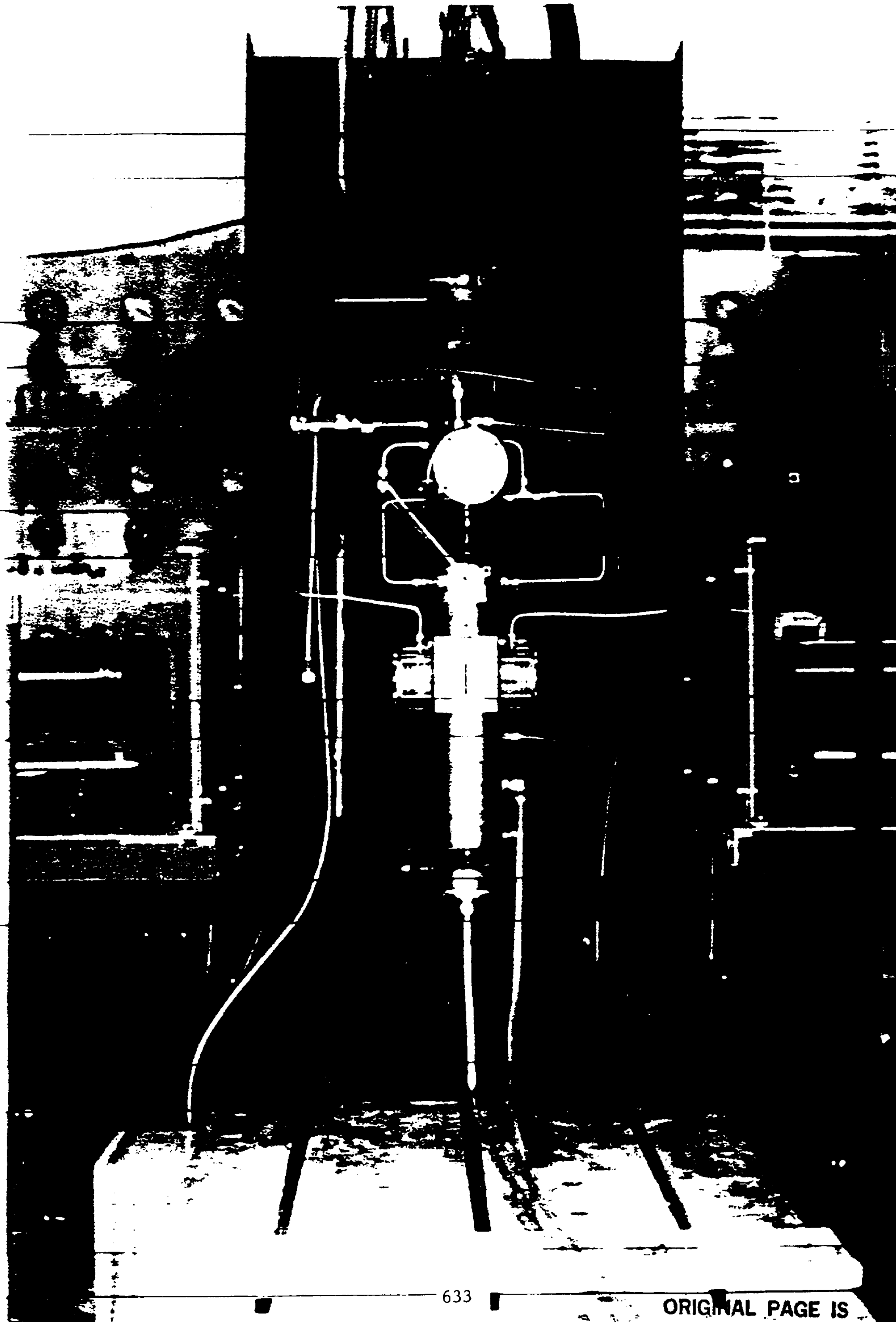
DROP SIZE PREDICTIONS

CORRELATION	DROP DIAMETER	DROP SIZE (μm) HOT FIRE[1]	DROP SIZE (μm) COLD FLOW[2]
NUKIYAMA (1939)	D_{32}	1227	2325
LORENZETTO (1977)	D_{32}	440	5856
WEISS (1959)	$D_{V0.5}$	1.88	12.9
MAYER (1961)	$D_{V0.5}$	0.39	4.25
ZALLER (1993)	D_{30}	4.8	64.9

MEASURED DROP SIZE

[1] HOT FIRE : $58 < D_{32} < 115$

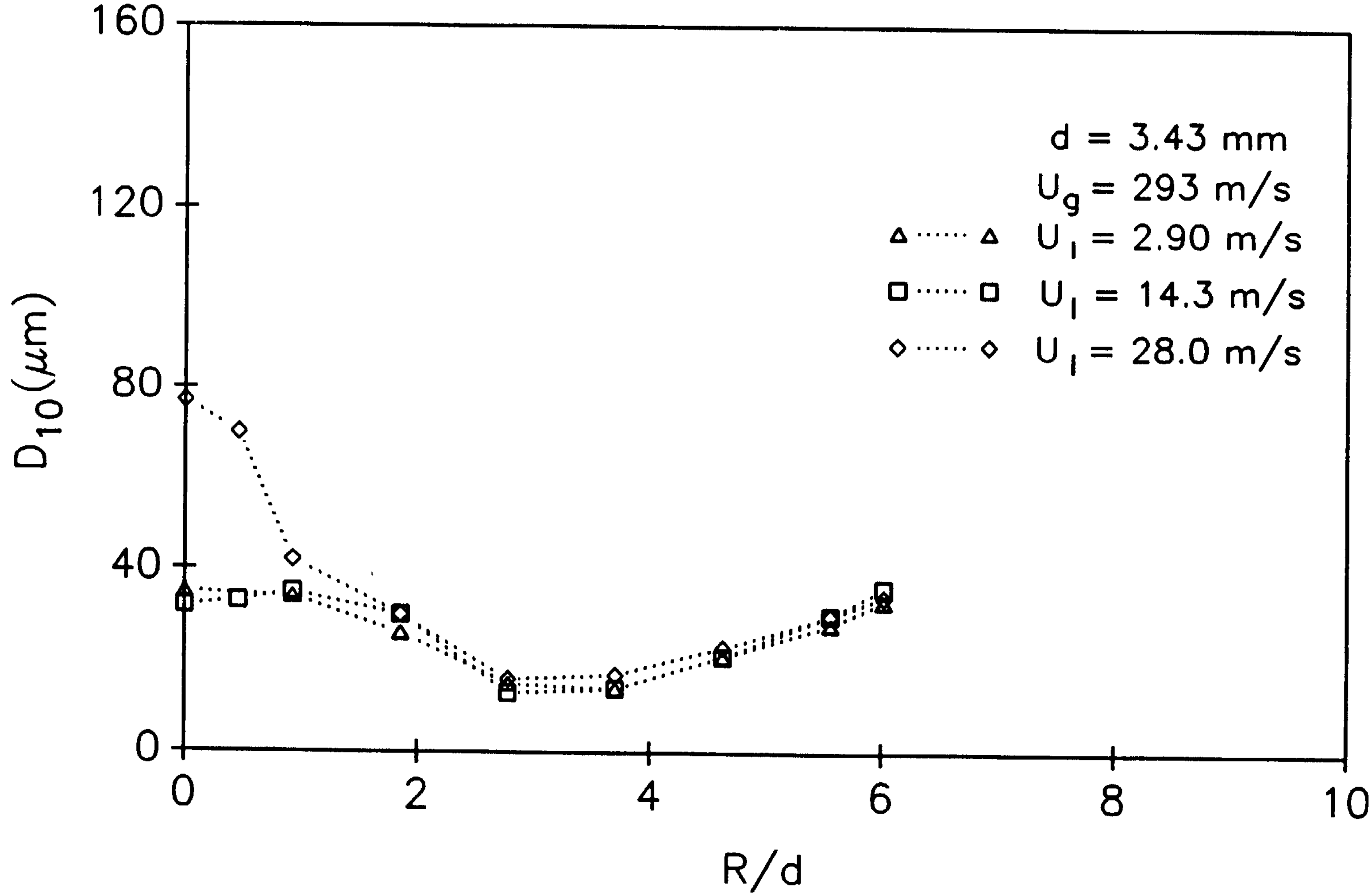
[2] COLD FLOW: $29 < D_{32} < 88$

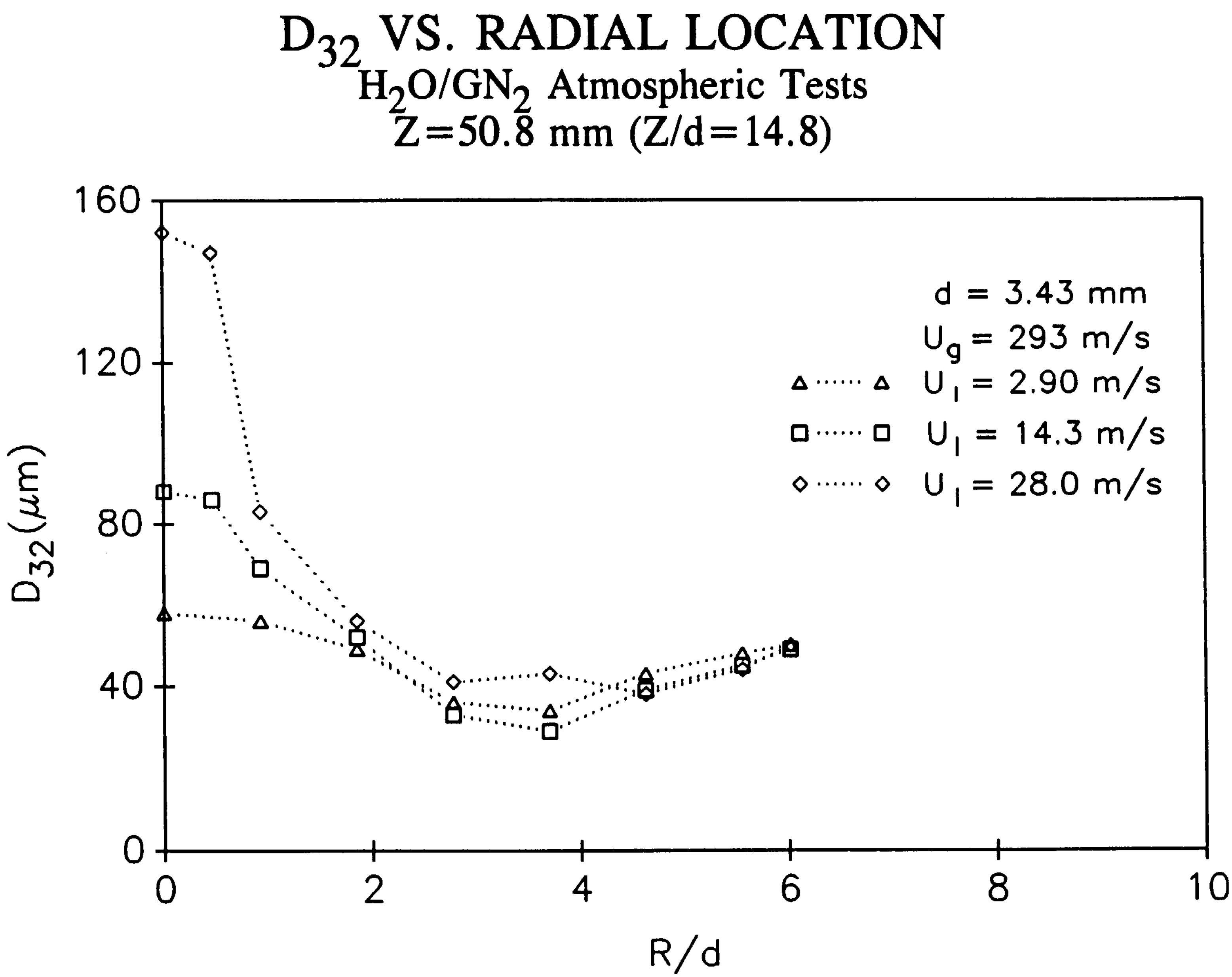


D_{10} VS. RADIAL LOCATION

H_2O/GN_2 Atmospheric Tests

Z=50.8 mm (Z/d=14.8)

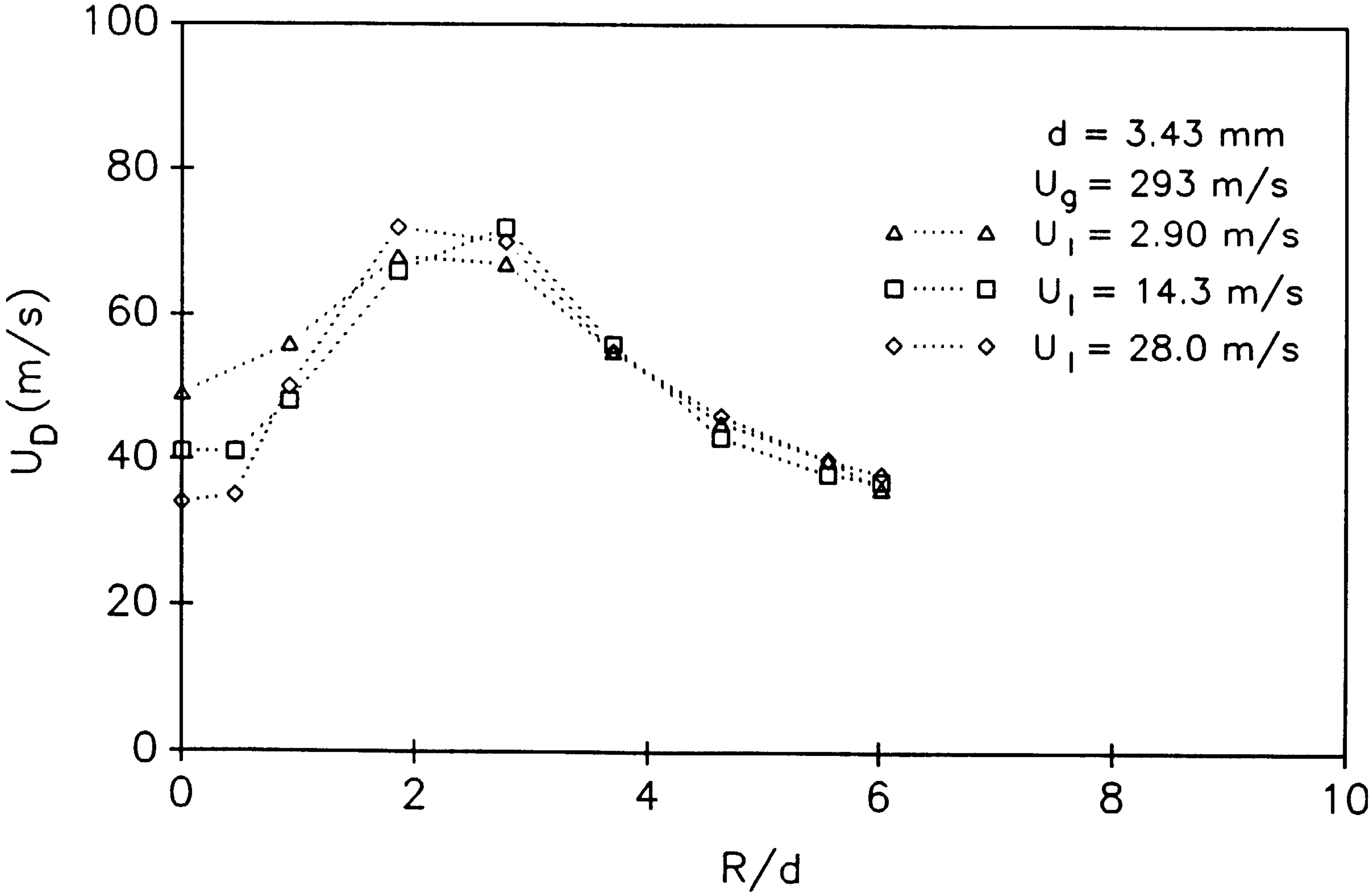



D32 VS. RADIAL LOCATION
H2O/GN2 Atmospheric Tests
Z=50.8 mm (Z/d=14.8)
d = 3.43 mm
Ug = 293 m/s
Ul = 2.90 m/s
Ul = 14.3 m/s
Ul = 28.0 m/s
D32 (μm)
160
120
80
40
0
0
2
4
6
8
10
R/d

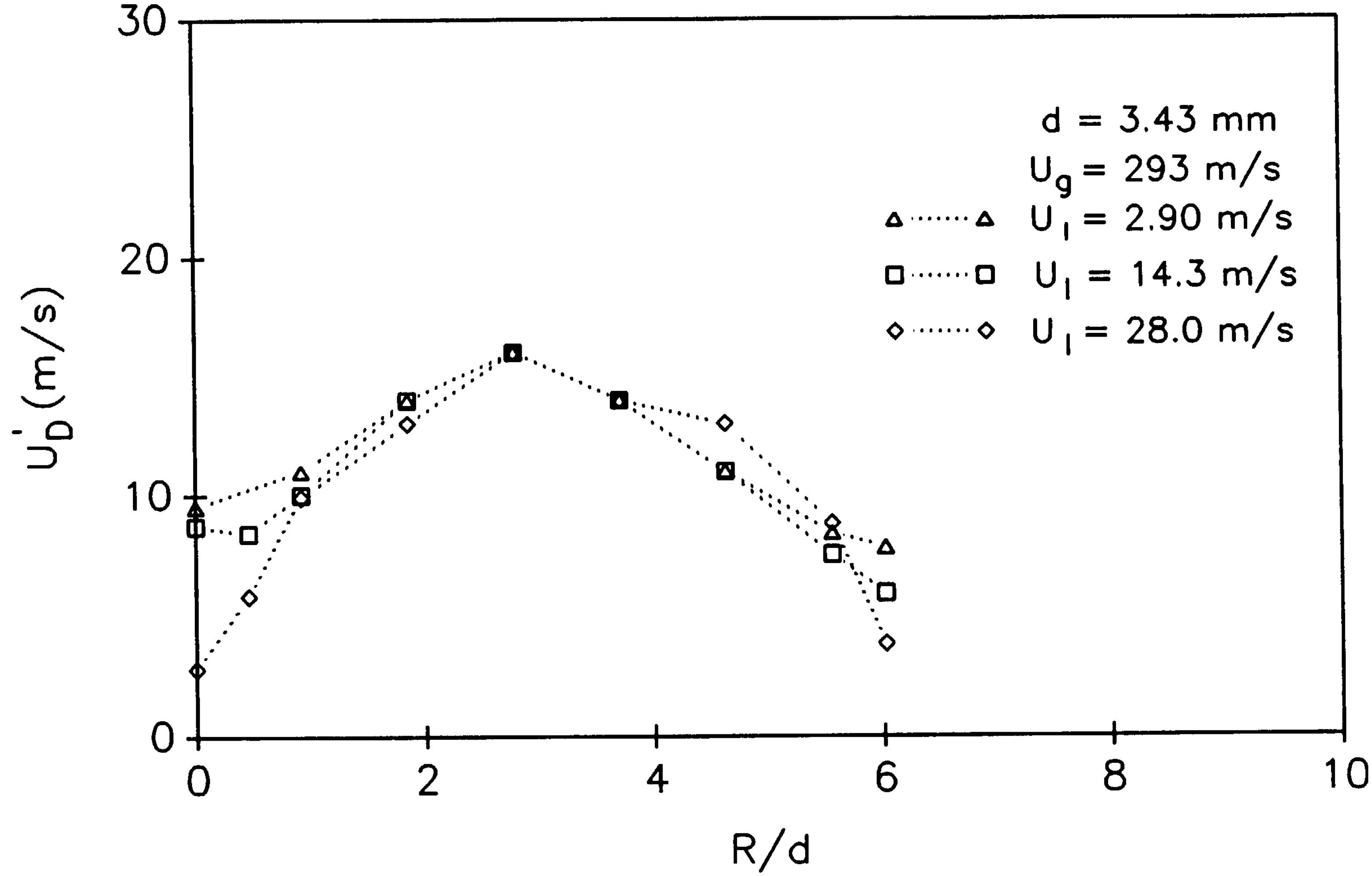
U_D VS. RADIAL LOCATION

H_2O/GN_2 Atmospheric Tests

Z=50.8 mm (Z/d=14.8)



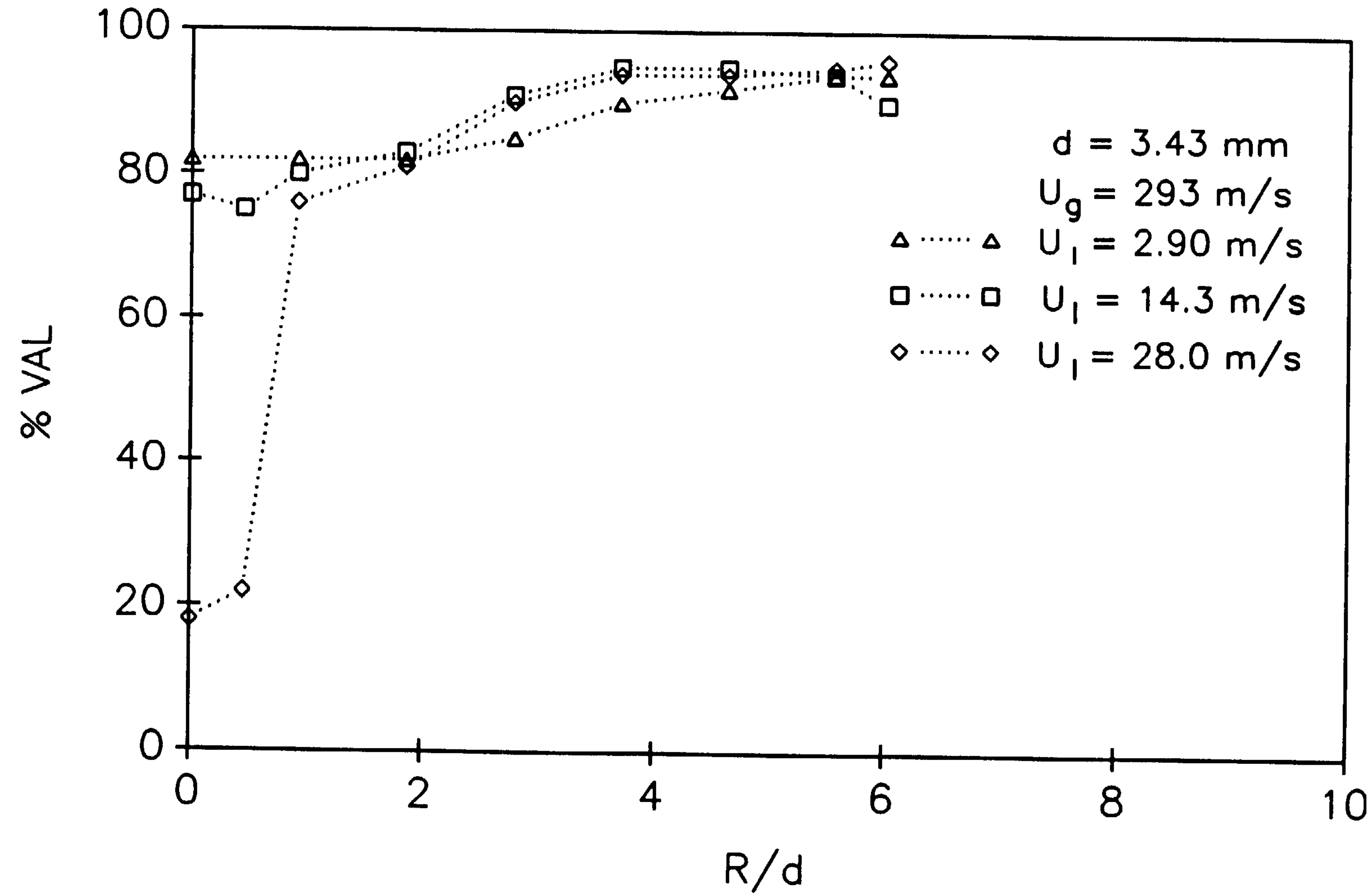
U_D' VS. RADIAL LOCATION
H_2O/GN_2 Atmospheric Tests
Z=50.8 mm (Z/d=14.8)



% VALIDATION VS. RADIAL LOCATION

H_2O/GN_2 Atmospheric Tests

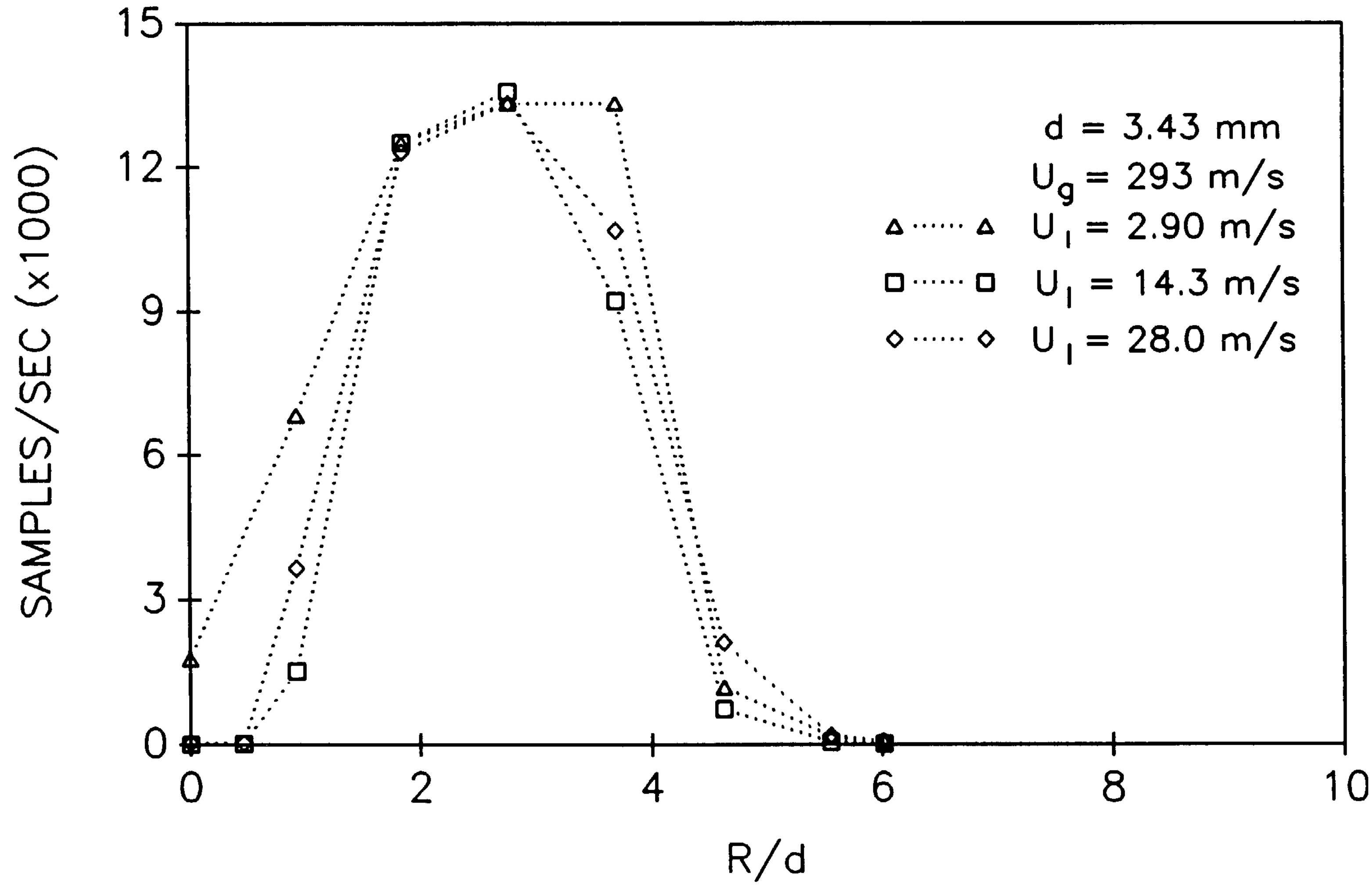
Z=50.8 mm (Z/d=14.8)



SAMPLES/SEC. VS. RADIAL LOCATION

H_2O/GN_2 Atmospheric Tests

$Z=50.8$ mm ($Z/d=14.8$)

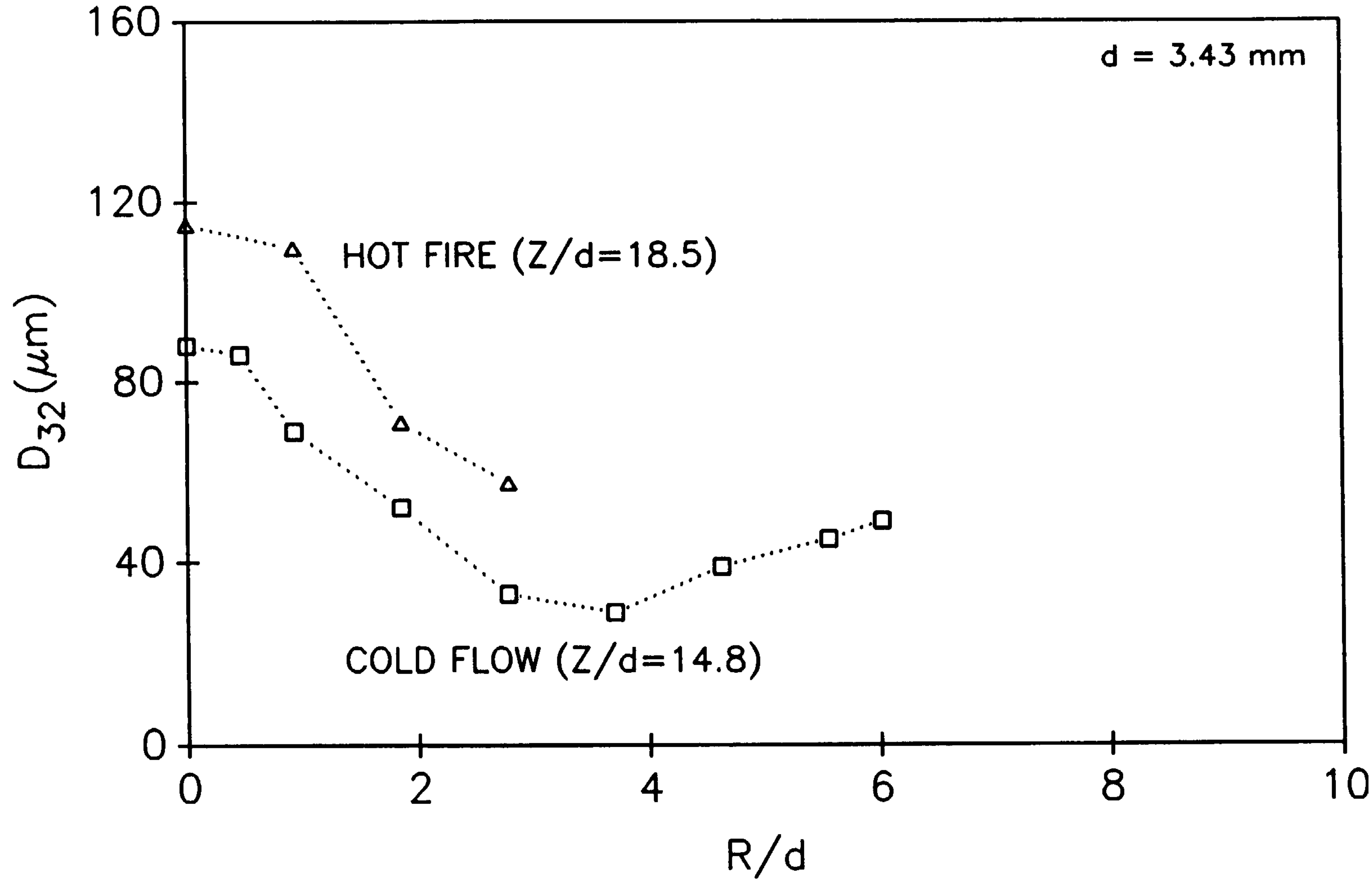


HOT FIRE/COLD FLOW COMPARISON

	HOT FIRE	COLD FLOW	RATIO (H.F./C.F.)
CHAMBER PRESSURE (psia)	387	14.7	26.3
LIQUID FLOWRATE (kg/s)	0.112	0.13	0.85
GAS FLOWRATE (kg/s)	0.021	0.009	2.3
MIXTURE RATIO (O/F)	5.4	14.5	0.37
LIQUID VELOCITY (m/s)	13.5	14.3	0.94
GAS VELOCITY (m/s)	381	290	1.3
VELOCITY RATIO (F/O)	28.3	20.3	1.4
Re_l ($=\rho_l U_l d/\mu_l$)	5.03×10^5	4.86×10^4	10.3
We_g ($=\rho_g (U_g-U_l)^2 d/\sigma$)	2.06×10^5	4.3×10^3	48

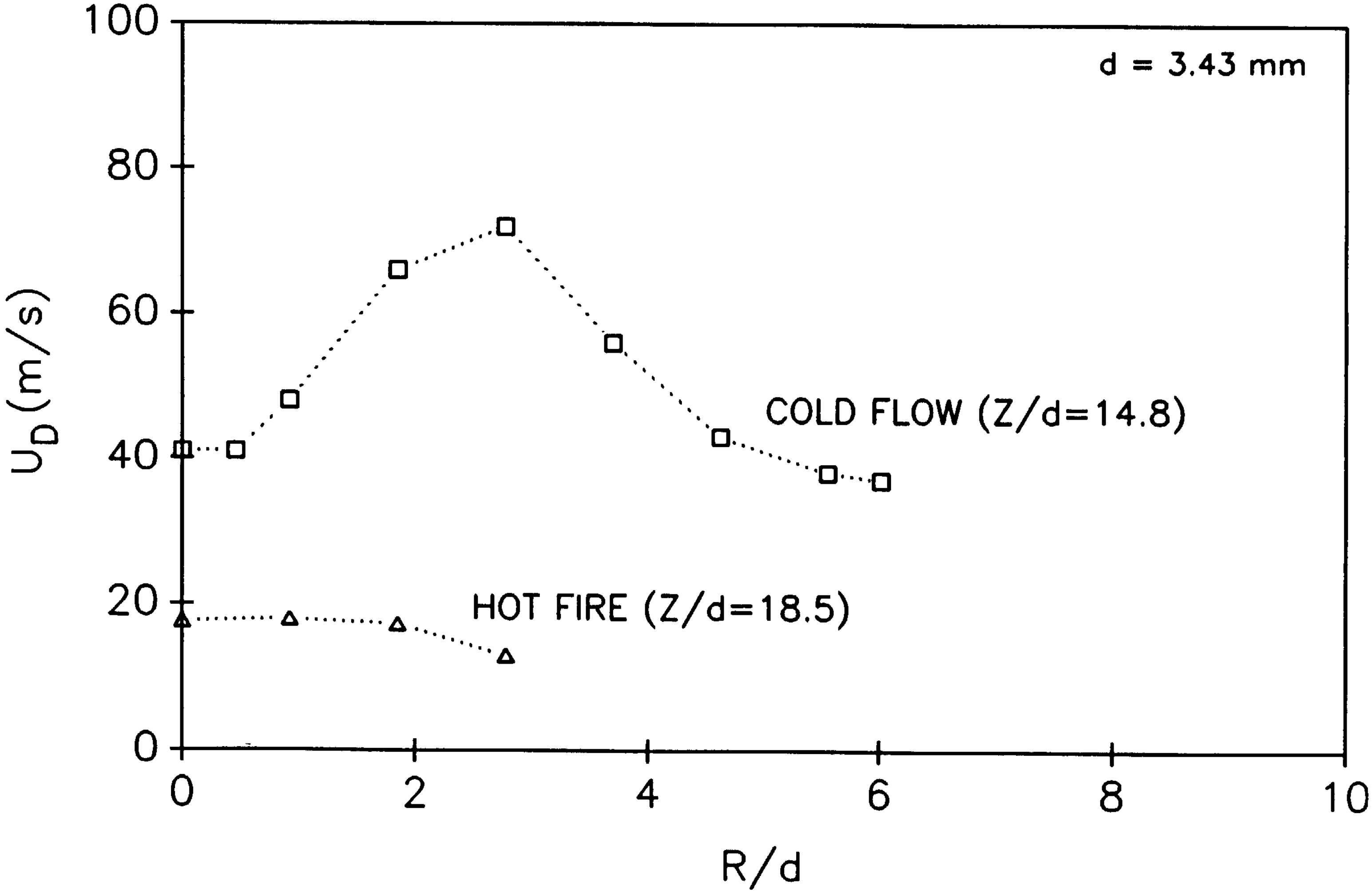
HOT FIRE/COLD FLOW COMPARISON

Sauter Mean Diameter (D_{32})



HOT FIRE/COLD FLOW COMPARISON

Mean Drop Velocity (U_D)



SUMMARY

- **Measured liquid oxygen drop size and velocity in combusting environment**

  - Intact core extends well beyond the injector

  - Drops confined to narrow region

- **Correlations based on cold flow data inadequate for predicting drop size in LOX/GH_2 combusting flow**

- **Compared drop measurements between cold flow and combusting conditions for similar liquid and gas flowrates**

  - Re_l and We_g differ by an order of magnitude

  - Mean drop size larger for hot fire conditions

ACKNOWLEDGEMENT

Funding by NASA Marshall Space Flight Center, contract NAS8-38862 and the Penn State NASA Propulsion Engineering Research Center, Contract NAGW 1356 supplement 2