COMBUSTION RESEARCH FACILITY

SAND2013-7480C

Experimental investigation of nozzle aspect ratio effects on underexpanded hydrogen jet release characteristics

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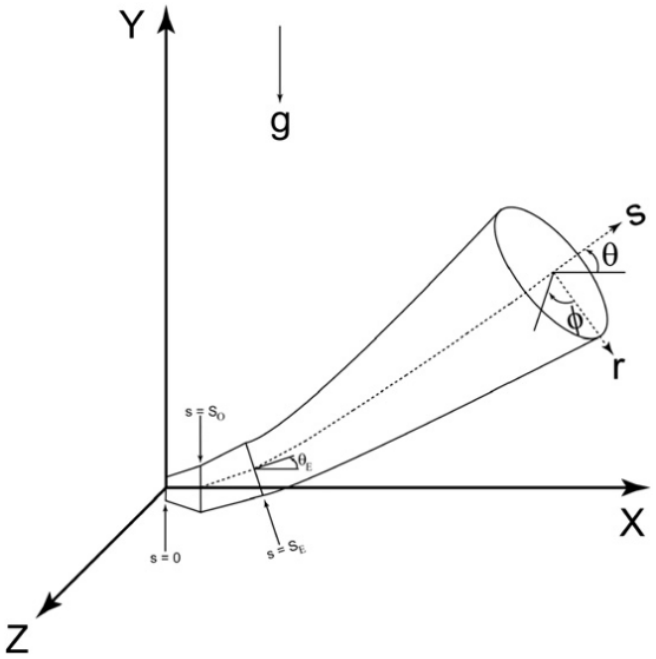
International Conference on Hydrogen Safety
Sept 9, 2013

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000

Circular free-jets have been well-characterized by simple integral models that invoke self-similarity



Reichardt, *VDI-Forschungsheft*, 1942

Jirka, *Environ Fluid Mech*, 2004
Houf & Schefer, *IJHE*, 2008
Winters & Houf, *IJHE*, 2010

Mass
$$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V r dr d\phi = \rho_{amb} E$$

x-Mom
$$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V^2 \cos\theta\, r dr\, d\phi = 0$$

y-Mom
$$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V^2 \sin\theta\, r dr d\phi = \int_0^{2\pi}\int_0^{\infty}(\rho_{amb}-\rho) g r dr d\phi$$

Species
$$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V Y r dr d\phi = 0$$

Energy
$$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V (h - h_{amb}) r dr d\phi = 0$$

Velocity & concentration profiles have linear inverse decay rates

Gaussian velocity, concentration, & excess state variable profiles

$$\frac{V}{V_{CL}} = \exp\left(-\frac{r^2}{B^2}\right)$$

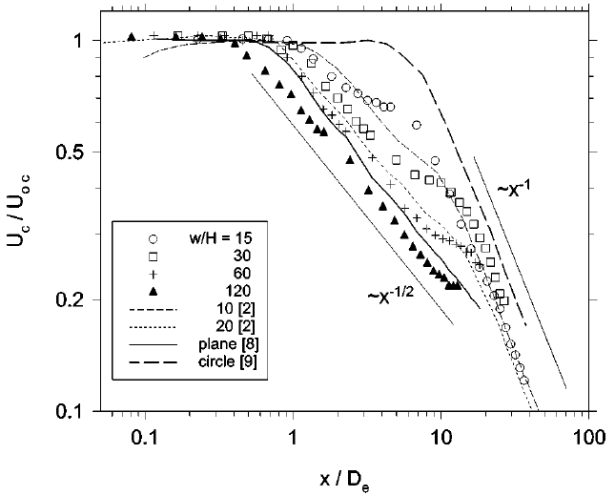
$$\frac{\rho Y}{\rho_{CL} Y_{CL}} = \exp\left(-\frac{r^2}{\lambda^2 B^2}\right)$$

$$\frac{X - X_{amb}}{X_{CL} - X_{amb}} = \exp\left(-\frac{r^2}{\lambda^2 B^2}\right)$$

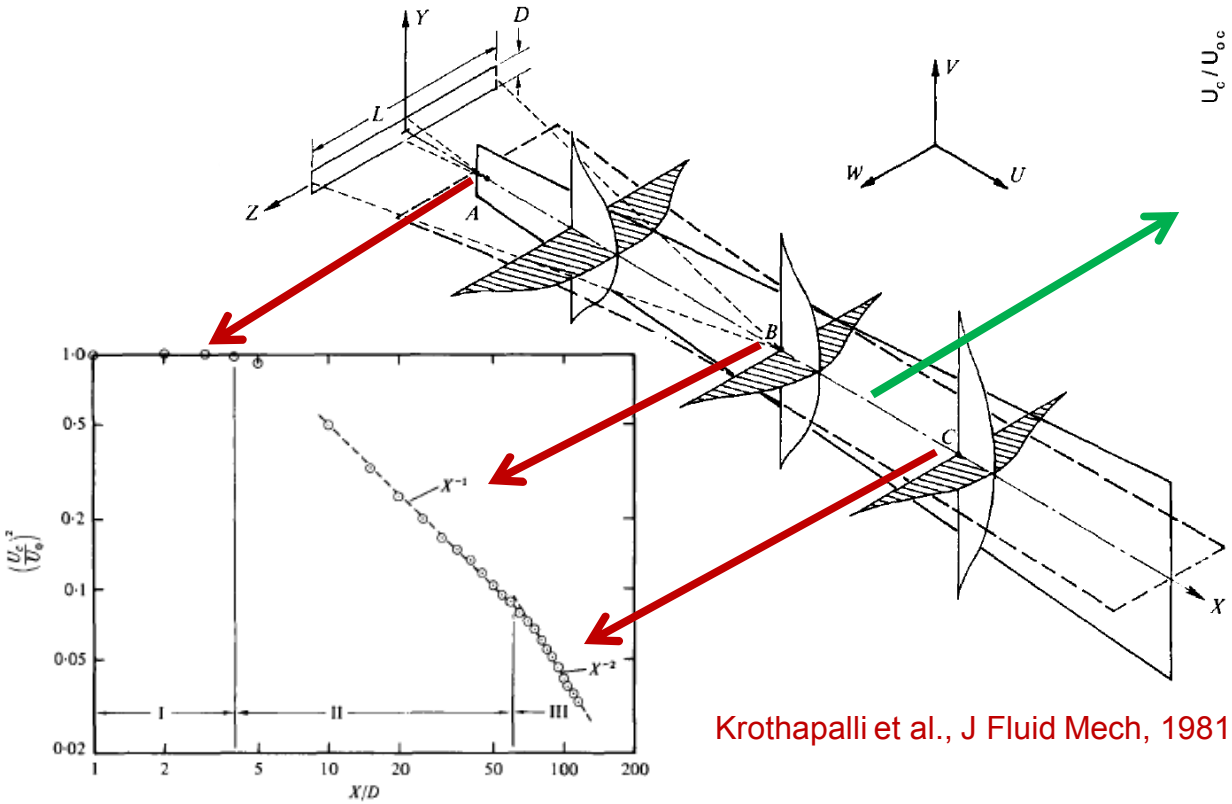
B: velocity jet width
λ: concentration-to-velocity jet width ratio
X: excess state variable

Unchoked slot jets have likewise been thoroughly investigated

Mi et al., Phys Fluids, 2005



Transition region between 2D & axisymmetric regions for jets w/ moderate AR

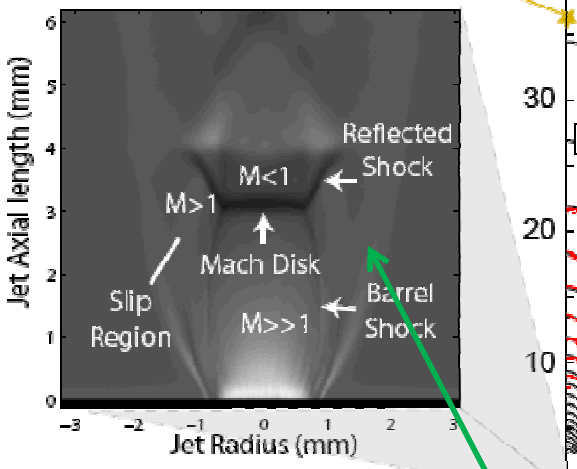


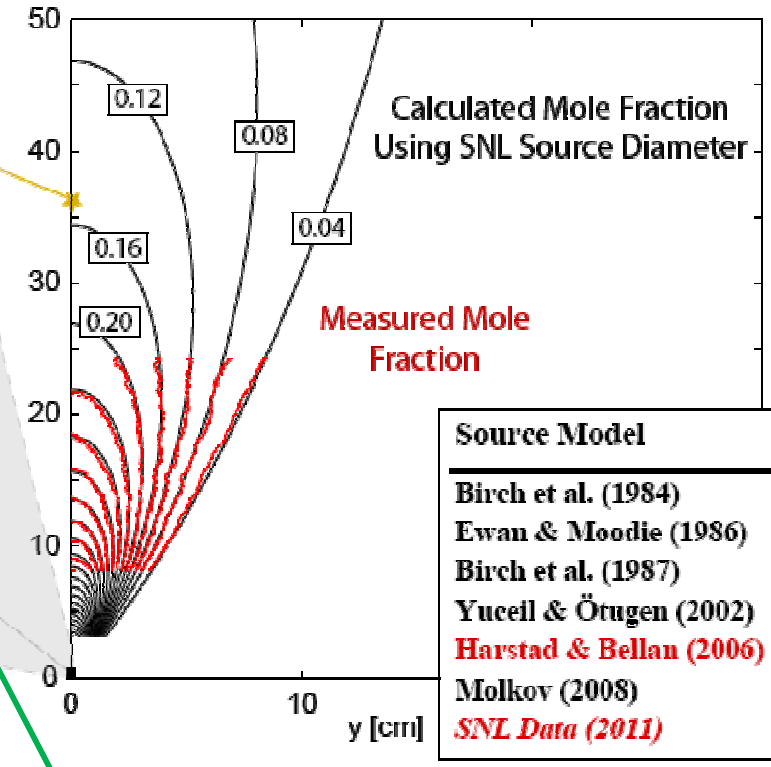
Krothapalli et al., J Fluid Mech, 1981

Distinct 2D region with an inverse half-power centerline decay rate exists between the initial and established flow regions

Large transition region extends well downstream of the source and cannot be neglected

Computed & measured mole fraction statistics agree if measured d^* is used as the scaling parameter





Ruggles & Ekoto, *IJHE*, 2012

$$d^* = d_{eff}\sqrt{\rho_{eff}/\rho_\infty}$$

Notional nozzle model outputs

Source Model	d^* [mm]
Birch et al. (1984)	0.947
Ewan & Moodie (1986)	0.993
Birch et al. (1987)	0.790
Yuceil & Ötugen (2002)	0.790
Harstad & Bellan (2006)	1.440
Molkov (2008)	0.993
SNL Data (2011)	*0.867*

Poor d^* prediction from all models

Stagnation Pressure: 10 bar
Nozzle Diameter: 1.5 mm

Most fluid appears to be in the slip region

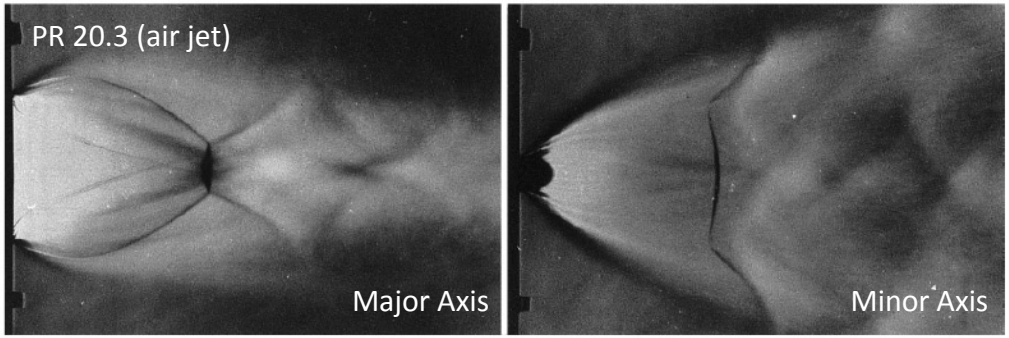
All models updated w/ Abel-Noble EOS

$$p = Z\rho RH_2T;\ Z = (1 - b\rho)^{-1}$$

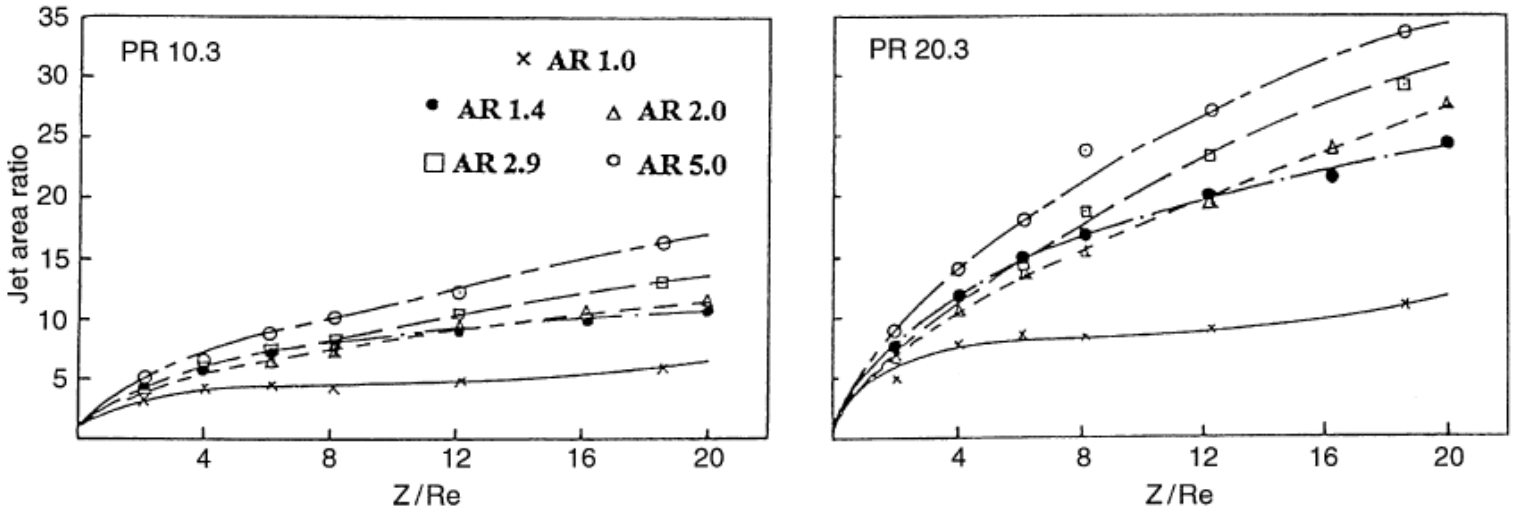
- Works well at ambient *T*
- Cryogenic states (T<100 K) poorly predicted

Analogous slot models do not exists due to a lack of downstream scalar/velocity validation data

Many leaks are non-circular: e.g., cracks, leaky fittings, ruptures



Rajakuperan & Ramaswamy, *Exp in Fluids*, 1998

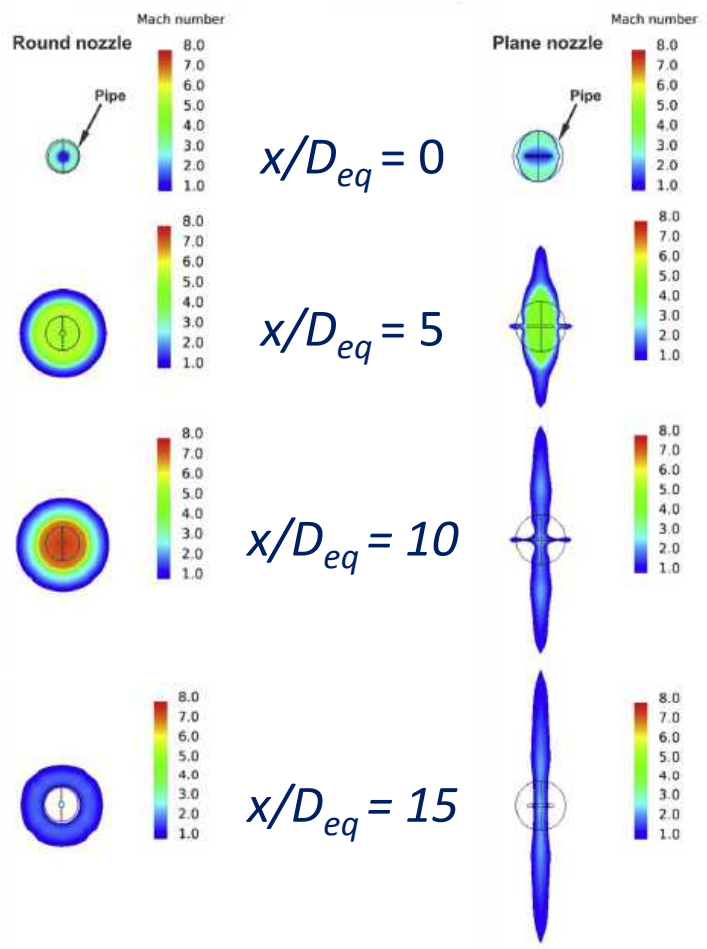


Elevated near field jet area ratios result in faster initial concentration decay rates

Axis switching due to faster minor axis jet spreading rates observed

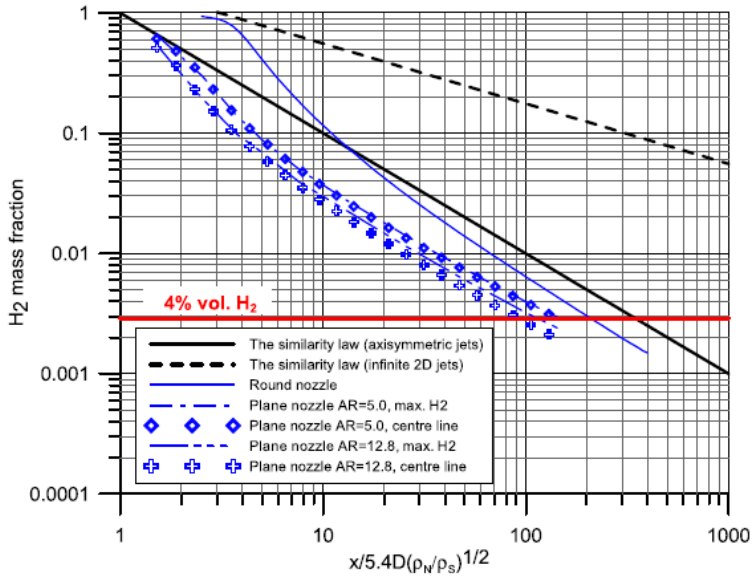
Axis switching phenomena observed for simulations of choked hydrogen slot jets

AR = 12.8



D_{eq} = 1.0 mm

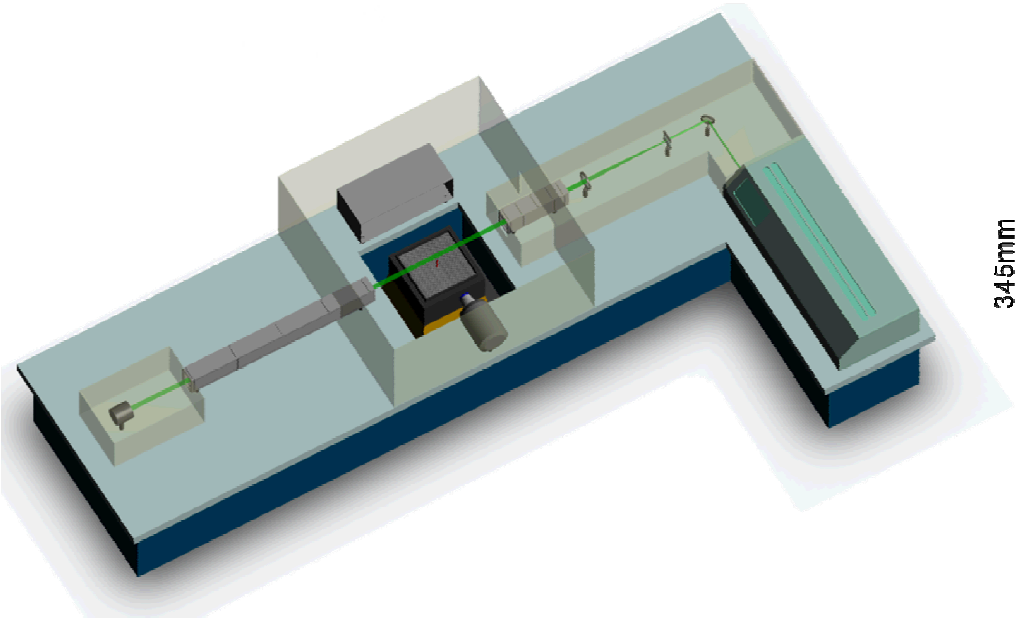
p_0 = 40 MPa

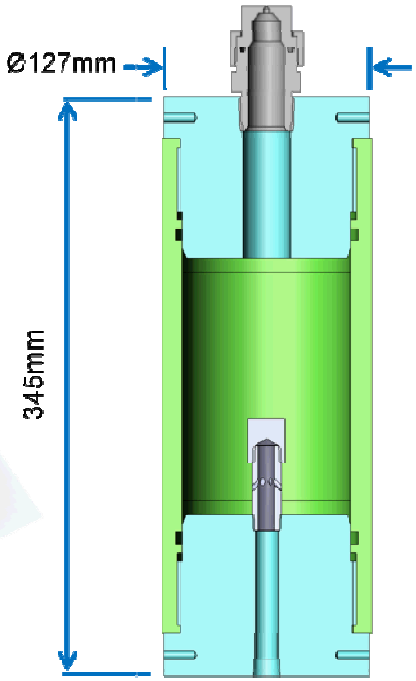


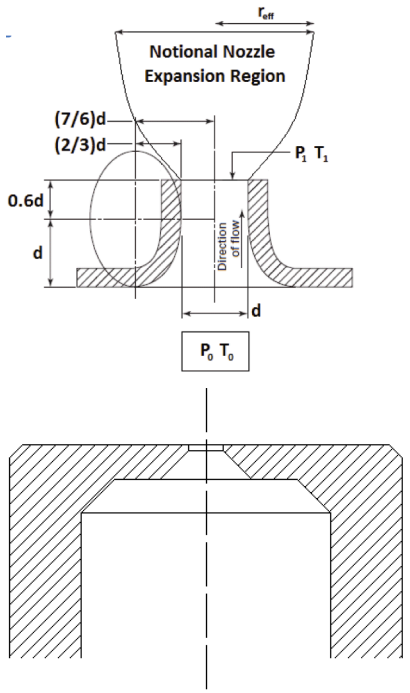
Makarov & Molkov, IJHE, 2013

Downstream scalar field measurements are needed to verify numerical observations and develop simplified 1D models

Downstream scalar field examined via high-resolution Planar Rayleigh Scatter Imaging (PLRS)







D_{eq} = 1.5 mm

p_0 = 10 bar

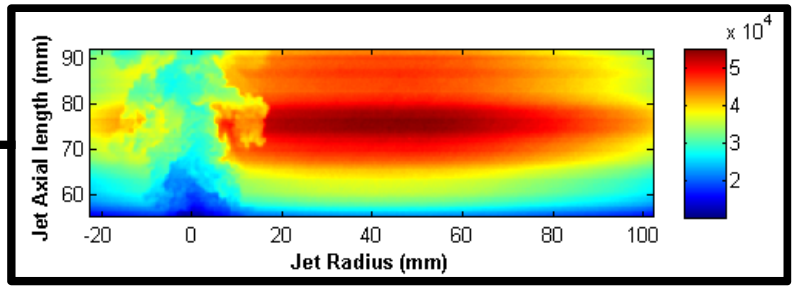
AR = 1, 2, 4 & 8

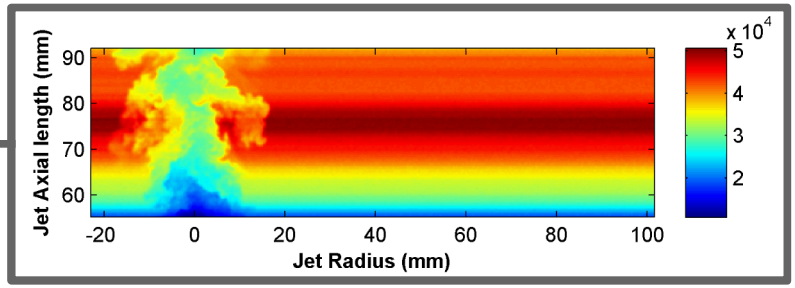
Schlieren imaging also performed to provide a qualitative description of the underexpanded jet exit shock structure

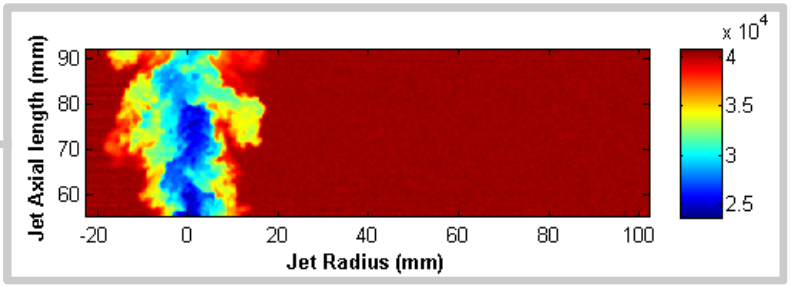
Signal intensity corrections used to create quantitative concentration image

R:	Raw image
E_B:	Electronic bias
B_G:	Background luminosity
p_F:	Laser power fluctuation
O_R:	Camera/lens optical response
S_B:	Background scatter
S_t:	Laser sheet profile variation
I:	Corrected intensity

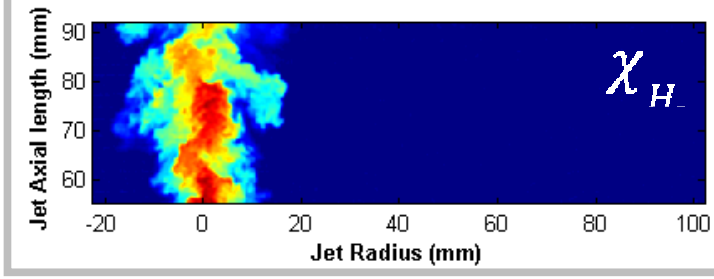
$$R = p_F \cdot O_R \cdot (I \cdot S_t + S_B) + E_B + B_G$$



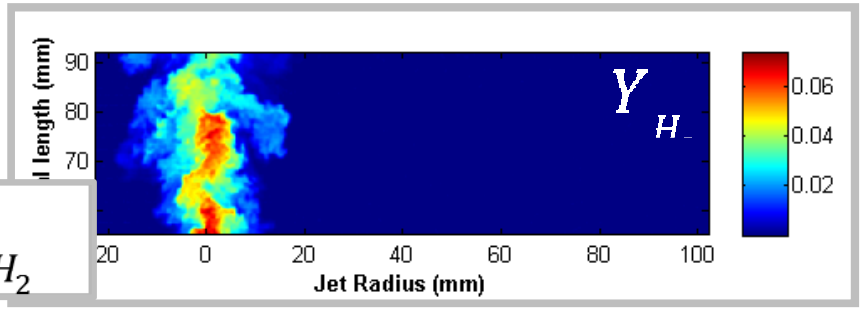




Mole Fraction $\chi_{H_2} \propto I$

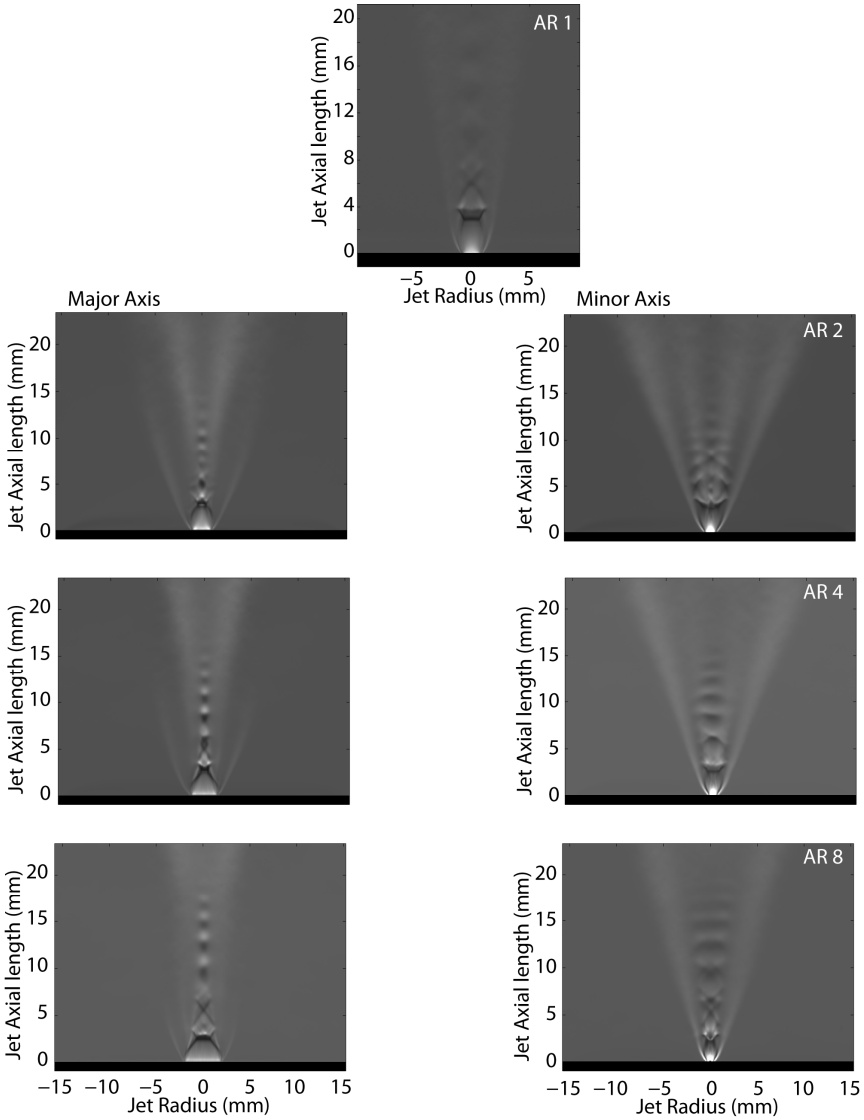


$Y_{H_2} \propto \chi_{H_2}$



Similar corrections performed for the schlieren images

Schlieren images indicate initial jet spreading rates are faster along minor axis

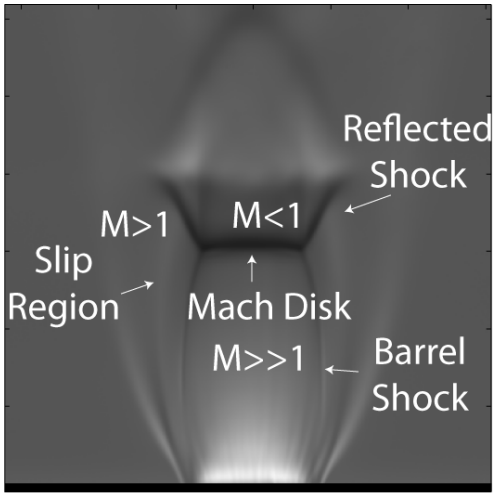


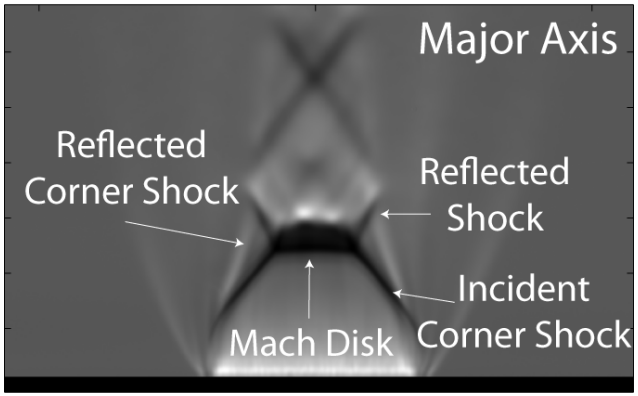
Downstream oblique shock structure disappears ~12-17 mm downstream

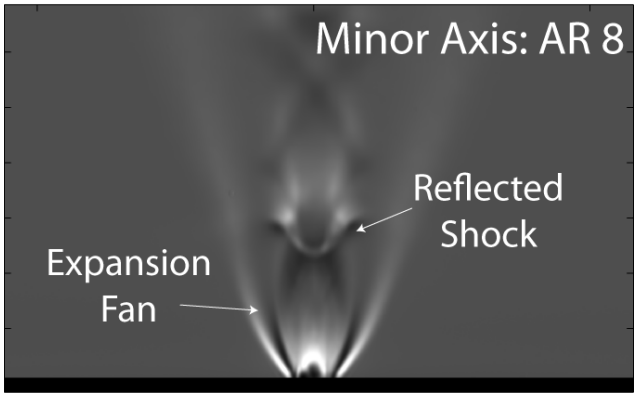
D_{eq} = 1.5 mm

p_0 = 10 bar

Close-up schlieren imaging reveals unique slot nozzle behavior

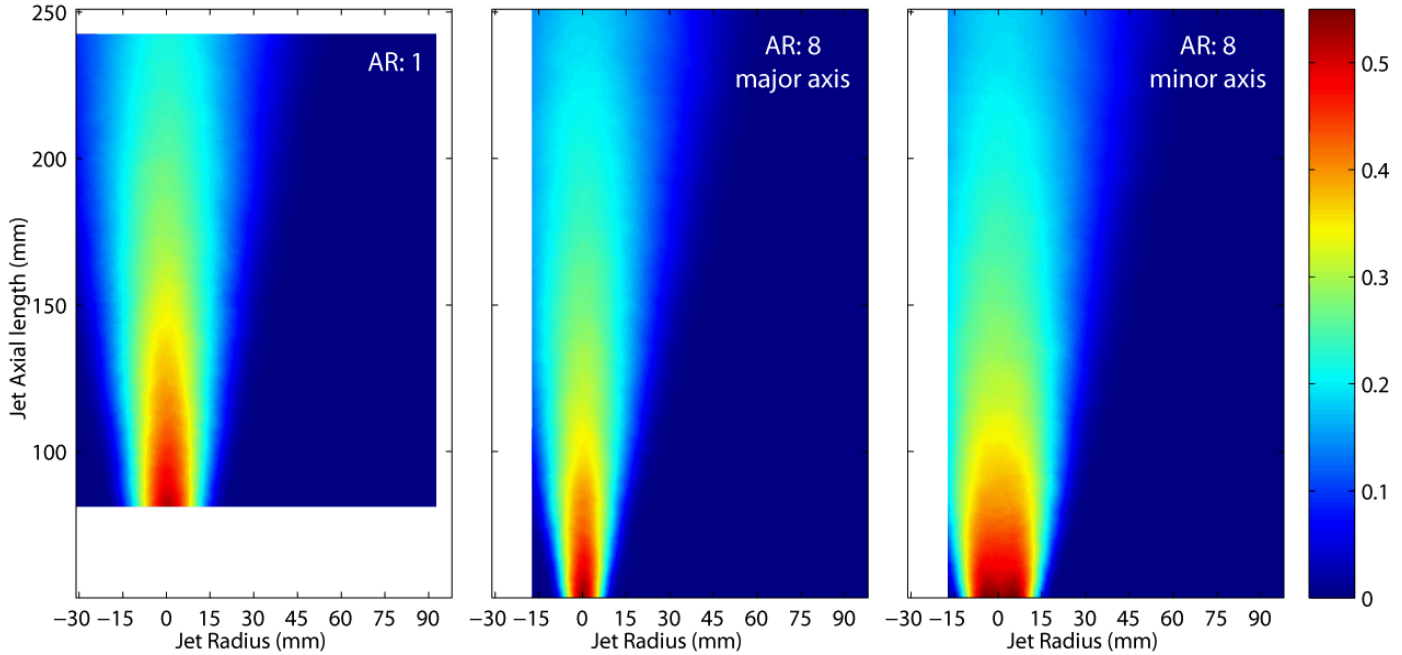






Evidence of the strong, sharply converging incident corner shock is missing from the minor axis plane

Mean mass fraction slot jet contours confirm axis switching in the scalar field



D_{eq} = 1.5 mm

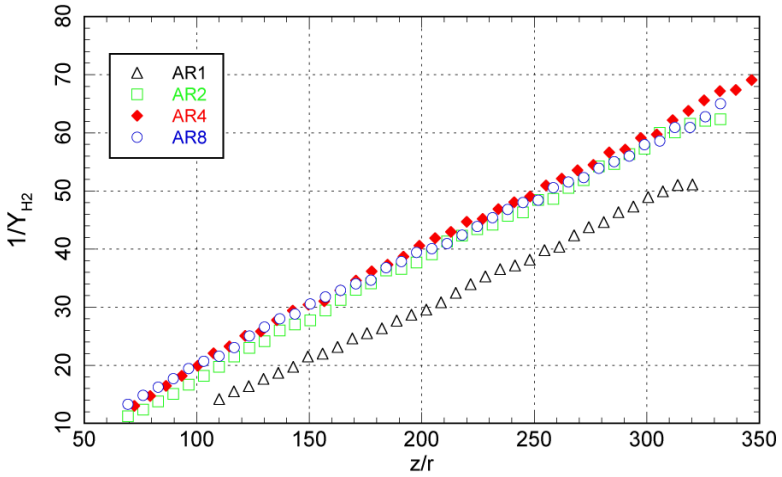
p_0 = 10 bar

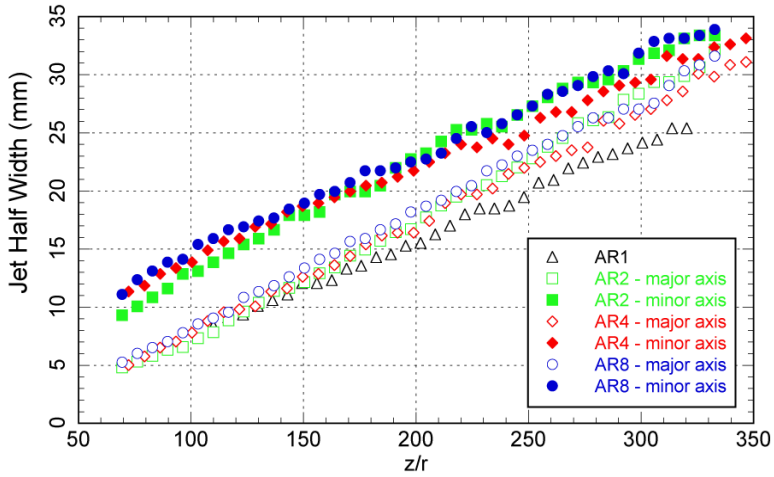
Elevated mass fraction contours extend further downstream for the ***axisymmetric*** jet

Concentration decay rates remained relatively linear throughout the measurement region

Evidence of a 2D region with an inverse half-power decay rate was not observed

- Likely upstream of the interrogation region





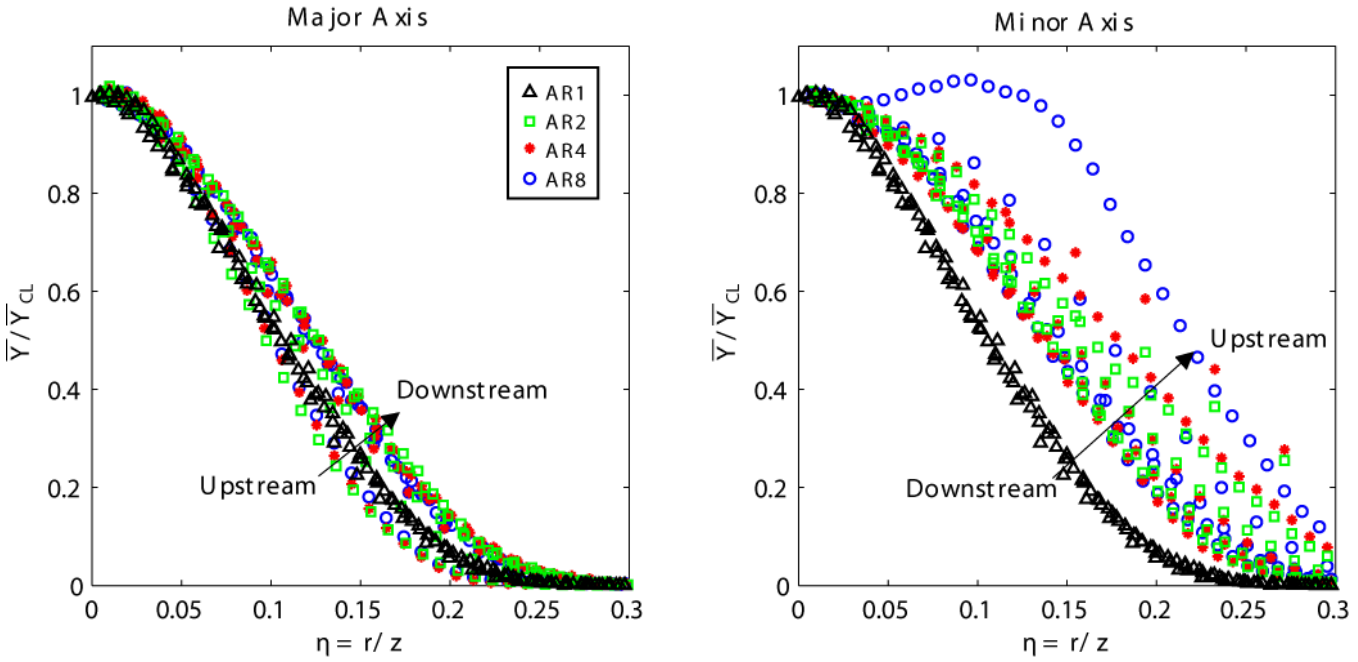
Major and minor axis jet half widths appear to converge

- Both half widths remained as large or larger than the corresponding axisymmetric jet
- Unclear when convergence will occur due to slightly non-linear growth rates

Normalized mean concentration radial profiles did not collapse to uniform curves for the major/minor axes

As expected, axisymmetric profiles collapsed to uniform curves

Normalized profiles grew ***slightly wider along the major axis*** and ***narrower along the minor axis***



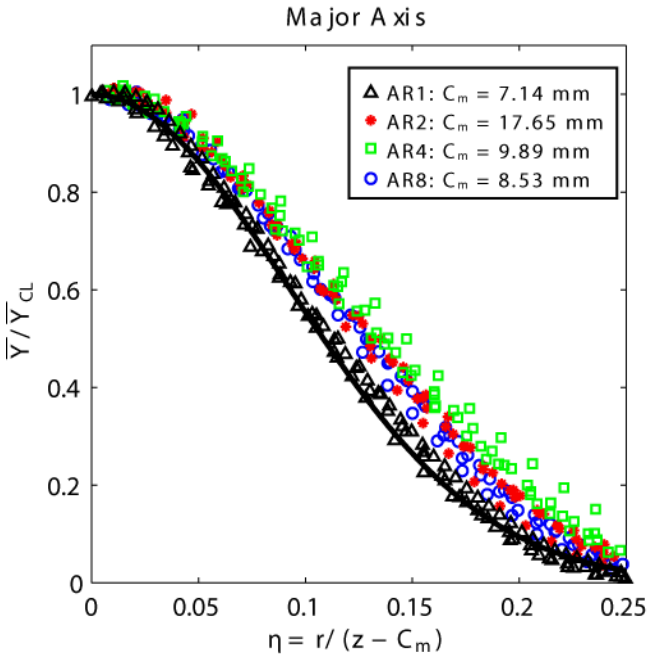
z/D_{eq} = 35, 69, 102, 136 & 161

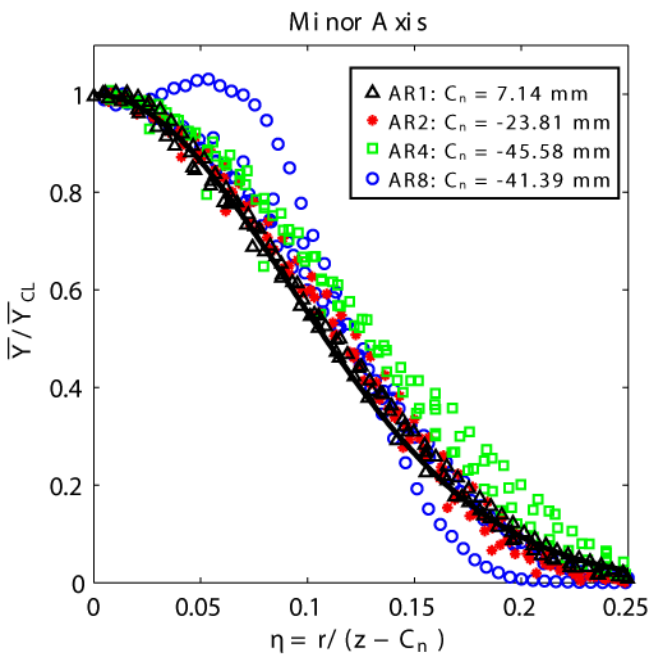
Peak H_2 ***near-field*** concentrations observed away from the centerline along the minor axis

Virtual coordinates used to provide a best fit collapse to uniform profiles along both axes

Self-similar collapse observed outside of the near-field

Collapsed profiles deviated from the axisymmetric values and were no longer Gaussian





z/D_{eq} = 35, 69, 102, 136 & 161

Results suggest it should be possible to develop a modified slot jet integral model — remains unclear for lager storage pressures & aspect ratios

Summary:

Schlieren images indicate faster minor axis initial jet spreading rates

- Possibly due to the absence of a sharply converging incident corner shock

Axis switching confirmed in the scalar measurements

- No evidence of 2D half-power decay region observed (likely upstream of interrogation region)
- Major/minor axes have slightly non-linear growth rates and appear to converge just outside of interrogation region

Normalized mean concentration radial profiles did not collapse to uniform curves for the major/minor axes

- Profiles grew slightly wider along the major axis and narrower along the minor axis
- Peak H_2 near-field minor axis concentrations observed away from the centerline
- If a virtual coordinate is used, far-field profiles collapsed to non-Gaussian profile

Limited results suggest it should be possible to develop a modified slot jet integral model — more research needed to confirm trends

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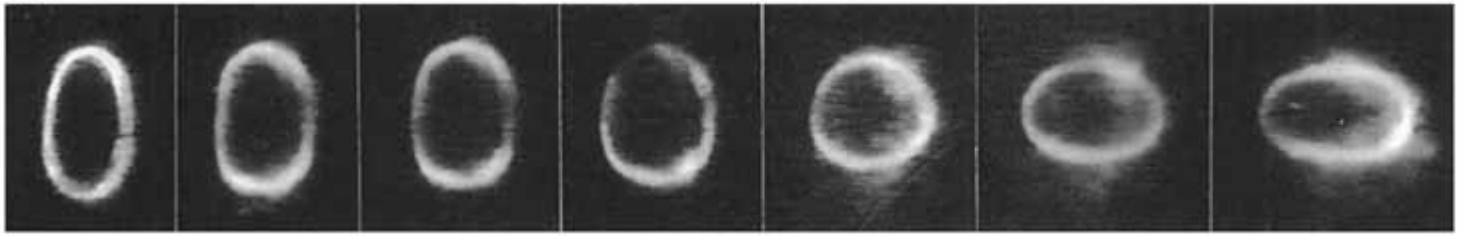
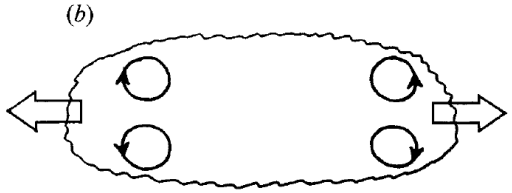
Axis switching phenomena has been observed for unchoked slot jets

Deformation and reorientation of rolled-up azimuthal vortices

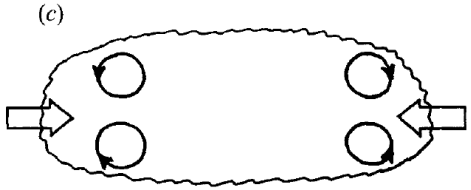


Hussain, *J Fluid Mech*, 1989

Induced streamwise vortex pairs



No axis switching



Axis switching

Zaman, *J Fluid Mech*, 1996