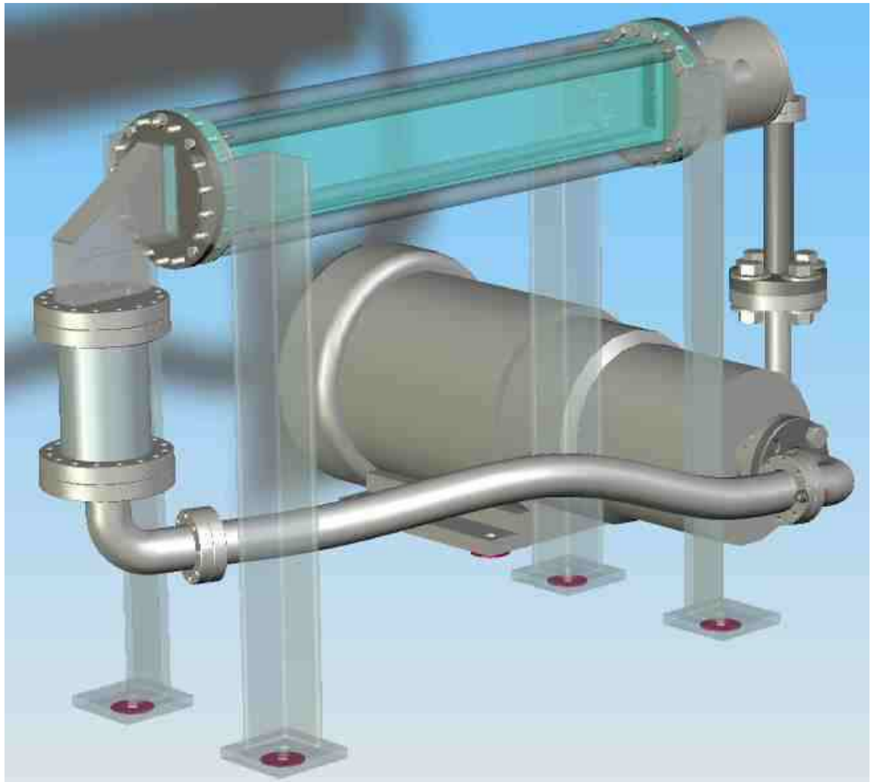
Nozzle R&D for a 20-m/s, 1-cm-diameter Mercury Jet



K.T. McDonald

Princeton U.

MERIT Collider Collaboration Meeting, MIT

October 19, 2005

http://puhep1.princeton.edu/mumu/target/

Mercury Jet Parameters

- **Diameter d = 1 cm.**
- **Velocity v = 20 m/s.**
- **The volume flow rate of mercury in the jet is**

$$\textbf{Flow Rate} = vA = 2000 \text{ cm/s} \cdot \frac{\pi}{4} d^2 = 1571 \text{ cm}^3/\text{s} \; = \; 1.57 \textbf{ l/s} = 0.412 \textbf{ gallon/s} \\ = \; 94.2 \textbf{ l/min} = 24.7 \textbf{ gpm}. \qquad (1)$$

- **The power in the jet (associated with its kinetic energy) is**

$$\textbf{Power} = \frac{1}{2}\rho \cdot \textbf{Flow Rate} \cdot v^2 = \frac{13.6 \times 10^3}{2} \cdot 0.00157 \cdot (20)^2 = 4270 \text{ W} = 5.73 \textbf{ hp}. \qquad (2)$$

- **To produce the 20-m/s jet into air/vacuum out of a nozzle requires a pressure**

$$\textbf{Pressure} = \frac{1}{2}\rho v^2 = 27.2 \textbf{ atm} = 410 \textbf{ psi}, \qquad (3)$$

  IF no dissipation of energy.

- **The mercury jet flow is turbulent: the viscosity is $\mu_{\rm Hg} = 1.5$ cP (kinematic viscosity $\eta = \mu/\rho = 0.0011$ cm^2/s), so the Reynolds number is**

$$\mathcal{R} = \frac{\rho d v}{\mu} = \frac{dv}{\eta} = 1.8 \times 10^6. \qquad (4)$$

- **The surface tension of mercury is τ = 465 dyne/cm (water = 73), $\Rightarrow$**

$$\textbf{Weber number, } \mathcal{W} = \frac{\rho d v^2}{\tau} = 115,000, \qquad \textbf{Ohnesorge number, } \mathcal{O} = \frac{\rho d v^2}{\tau} = 0.015. \qquad (5)$$

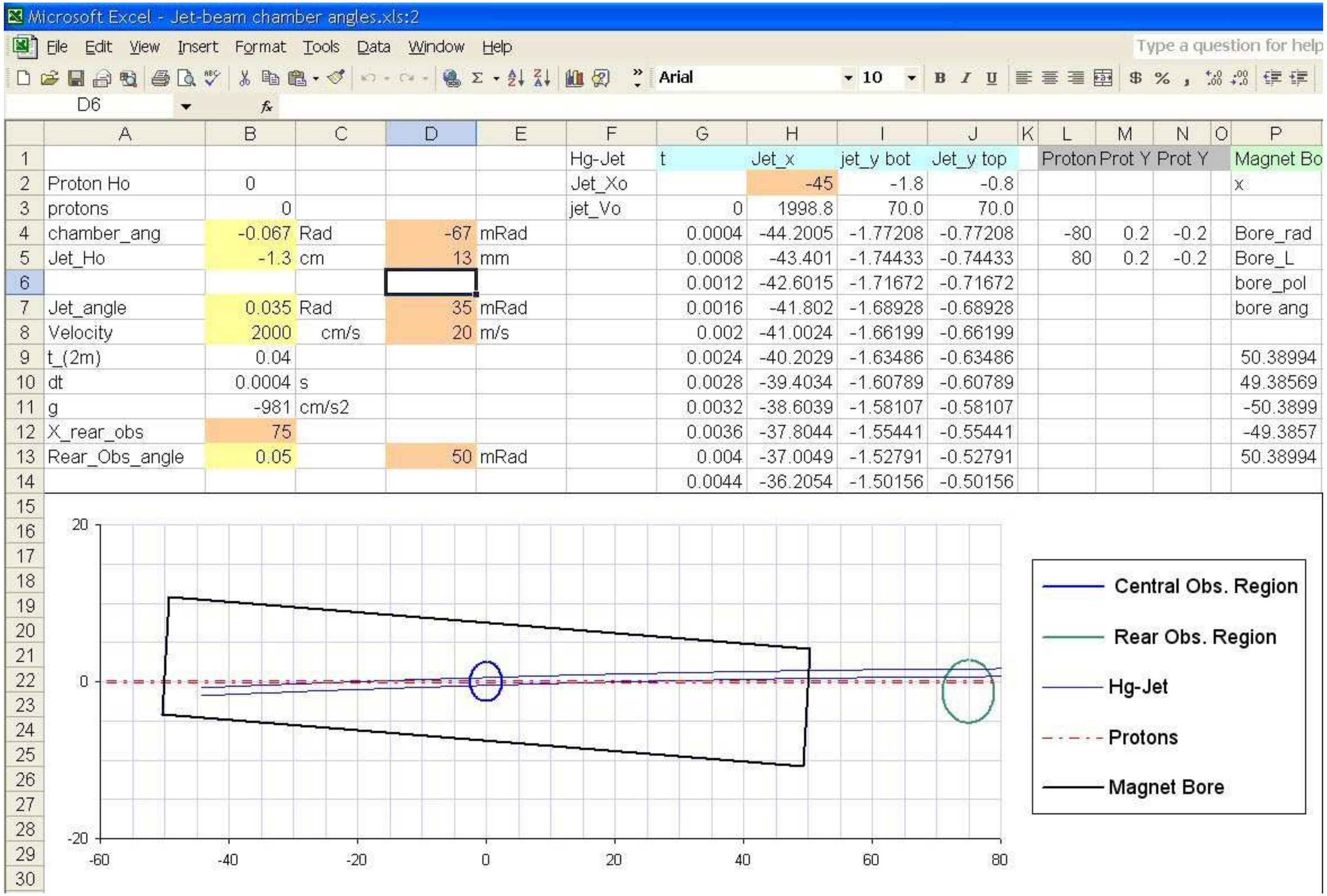
- **The electrical conductivity of mercury is** $\sigma_{\rm Hg} = \sigma_{\rm Cu}/60 = 9 \times 10^{15}$ $\mathbf{s^{-1}}$**,** $\Rightarrow$

$$\textbf{Hartmann number, } \mathcal{M} = \frac{B_\perp d}{c}\sqrt{\frac{\sigma}{\eta\rho}} = 270, \qquad \textbf{assuming } B_\perp = 10,000 \ \mathbf{G},$$

$$\textbf{Magnetic Reynolds number, } \mathcal{R}_M = \frac{\sigma v d}{c^2} = 0.02. \tag{6}$$

Mercury Jet + Proton Beam + 15-T Solenoid Magnet

J. Lettry:



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1						Hg-Jet	t	Jet_x	jet_y bot	Jet_y top		Proton	Prot Y	Prot Y		Magnet Bo
2	Proton Ho	0				Jet_Xo		-45	-1.8	-0.8						x
3	protons	0				jet_Vo	0	1998.8	70.0	70.0						
4	chamber_ang	-0.067	Rad	-67	mRad		0.0004	-44.2005	-1.77208	-0.77208		-80	0.2	-0.2		Bore_rad
5	Jet_Ho	-1.3	cm	13	mm		0.0008	-43.401	-1.74433	-0.74433		80	0.2	-0.2		Bore_L
6							0.0012	-42.6015	-1.71672	-0.71672						bore_pol
7	Jet_angle	0.035	Rad	35	mRad		0.0016	-41.802	-1.68928	-0.68928						bore ang
8	Velocity	2000	cm/s	20	m/s		0.002	-41.0024	-1.66199	-0.66199						
9	t_(2m)	0.04					0.0024	-40.2029	-1.63486	-0.63486						50.38994
10	dt	0.0004	s				0.0028	-39.4034	-1.60789	-0.60789						49.38569
11	g	-981	cm/s2				0.0032	-38.6039	-1.58107	-0.58107						-50.3899
12	X_rear_obs	75					0.0036	-37.8044	-1.55441	-0.55441						-49.3857
13	Rear_Obs_angle	0.05		50	mRad		0.004	-37.0049	-1.52791	-0.52791						50.38994
14							0.0044	-36.2054	-1.50156	-0.50156						

The centers of the mercury jet, the proton beam and the magnet should coincide.

The nozzle should be about 45 cm upstream of the center of the 15-cm-bore magnet.

Mercury jet comes up from below the proton beam at about 33 mrad.

The top of the nozzle must be at least 5 mm below the proton beam.

Mercury Jet Issues

Topics that can be studied without magnetic field:

- Choice of nozzle shape to keep jet together over 60 cm when B = 0.
- Attach the nozzle to a plenum (buffer volume)?
- Effect of gas pressure on jet stability.
- Possible backsplash of mercury by the downstream deflector.

Topics that can be only be studied with magnetic field:

- Effect of magnetic field on mercury delivery to the nozzle.
- Distortion of mercury jet by the magnetic field.

⇒ Final configuration of mercury jet can be chosen only after the systems tests at MIT in 2006.

Prior to that, nozzle R&D in zero magnetic field is underway at Princeton.

Some Nozzle Lore

From M.J. McCarthy and N.A. Molloy, *Review of Stability of Liquid Jets and the Influence of Nozzle Design*, Chem. Eng. J. 7, 1 (1974),
http://puhep1.princeton.edu/~mcdonald/examples/fluids/mccarthy_cej_7_1_74.pdf

By Ohnesorge's criterion, we are in a regime where the jet will break up into fine droplets (atomization), rather than into beads.

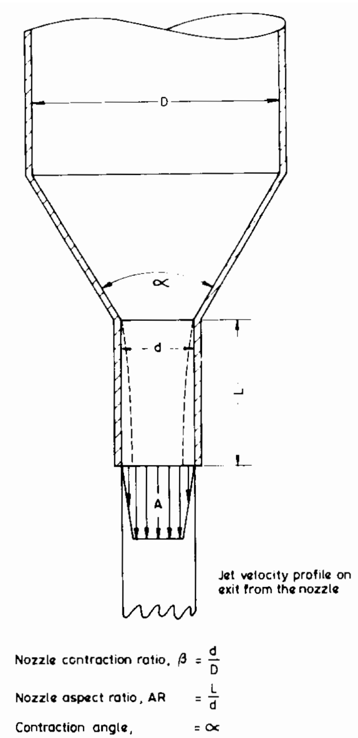
Empirical extensions of Weber's analysis for turbulent jets suggest that we could achieve a length L before breakup of $L \approx 8d\sqrt[3]{\mathcal{W}} = 370$ cm (290 cm for a water jet).

However, advice on nozzle design is not very definitive.

It seems good precede the nozzle by a larger inlet tube.

It may be better to have only a very short length at the final diameter of the nozzle.

Should the transition from a large-diameter inlet to a small-diameter nozzle be abrupt or gradual?



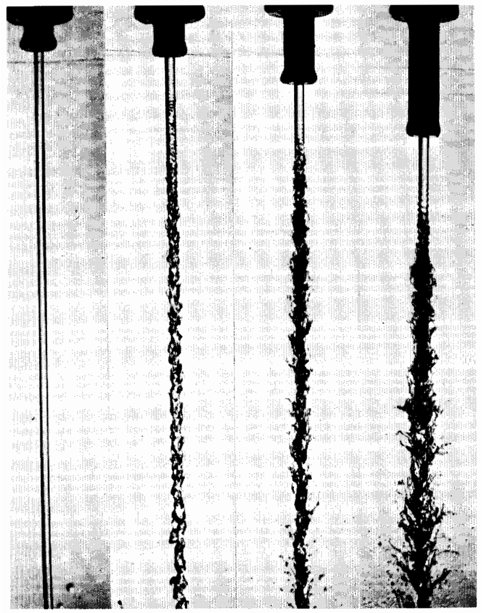


Fig. 5. Effect of nozzle design on the stability of glycerol–water jets.

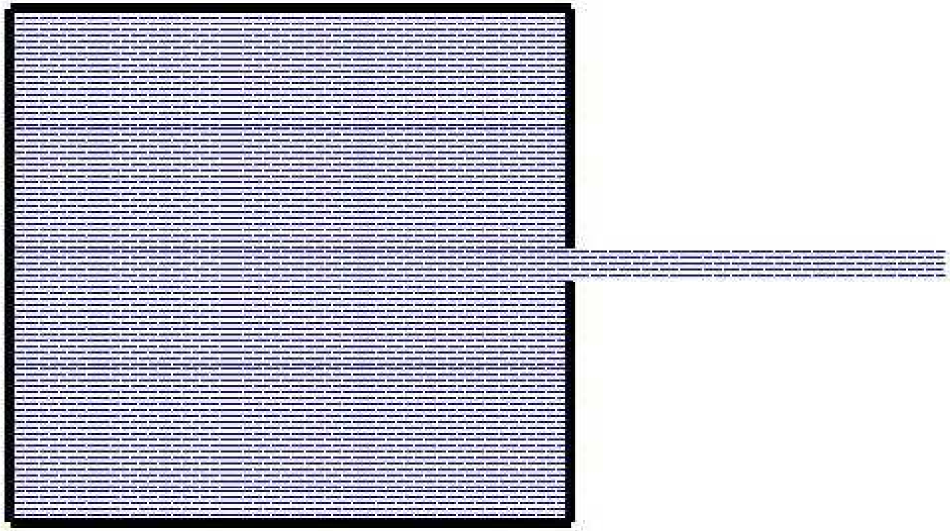
Jet viscosity	11 cP
Jet velocity	20 m s^{-1} (approx.)
Nozzle diameter	2.54 mm
Jet Reynolds no.	4750
Jet Ohnesorge no.	0.026
Exposure	30 μsec
Nozzle aspect ratio	$AR = L/d$ (see Fig. 7) = 0, 1, 5, 10 L to R.

The Best Nozzle is No Nozzle(?)

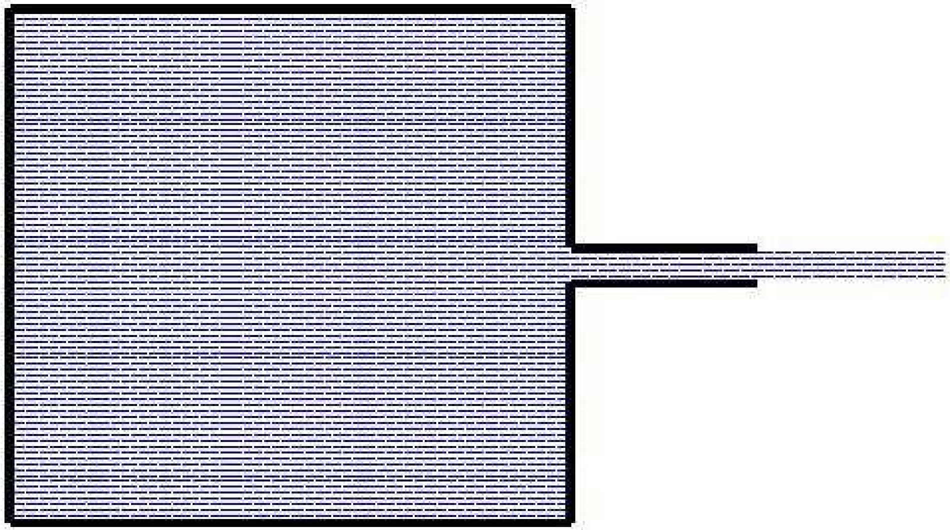
Reservoir at pressure P with small aperture:

$$v_{\mathrm{reservoir}} \approx 0, \qquad v_{\mathrm{jet}} \approx \sqrt{\frac{P}{\rho}}.$$

Jet emerges perpendicular to the plane of the aperture.



Reservoir + short nozzle:



No reservoir, just a straight tube.

$v_{\mathrm{jet}} = v_{\mathrm{tube}}$:

Most nozzle R&D is concerned with making a jet break up quickly and uniformly (atomization), rather than with preserving the jet.

Conservation of Energy *vs.* $\mathbf{F} = d\mathbf{P}/dt$ at a Contraction? (Borda, 1766)

Incompressible fluid $\Rightarrow V_1 A_1 = V_2 A_2$**.**

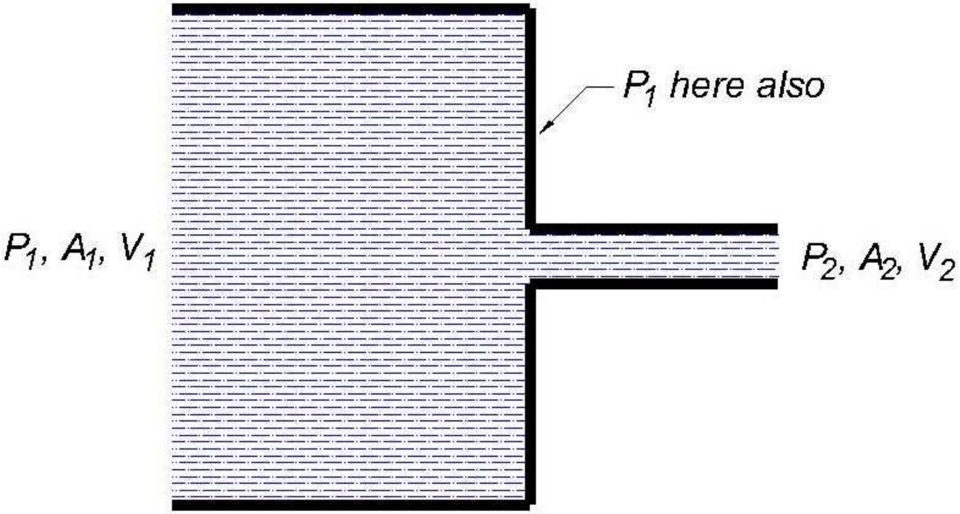
$$A_2 \ll A_1 \Rightarrow V_1 \ll V_2.$$

Conservation of Energy $\Rightarrow$ **Bernoulli's Law:**

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2.$$

$$V_1 \ll V_2 \Rightarrow \qquad V_2^2 \approx 2\frac{P_1 - P_2}{\rho}.$$

Argument does not depend on the area.



$\mathbf{F} = d\mathbf{P}/dt$**:**

Mass flux $= \rho V A$**.**

Momentum flux $= \rho V^2 A$**.**

Net momentum flux $= \rho(V_2^2 A_2 - V_1^2 A_1)$

$$= \rho V_2 A_2 (V_2 - V_1) \approx \rho V_2^2 A_2.$$

Force $\approx (P_1 - P_2) A_2$**.**

$$\mathbf{F} = \frac{d\mathbf{P}}{dt} \Rightarrow \qquad V_2^2 \approx \frac{P_1 - P_2}{\rho}.$$

Consistency $\Rightarrow$ **dissipative loss of energy, OR jet pulls away from the wall and contracts.**

Vena Contracta

Cavitation can be induced by a sharp-edged aperture.

A jet emerging from a small aperture in a reservoir contracts in area:

$$A_{\mathrm{jet}} = \frac{\pi}{\pi + 2} A_{\mathrm{aperture}} = 0.62 A_{\mathrm{aperture}}$$

$$d_{\mathrm{jet}} = 0.78 \; d_{\mathrm{aperture}}$$

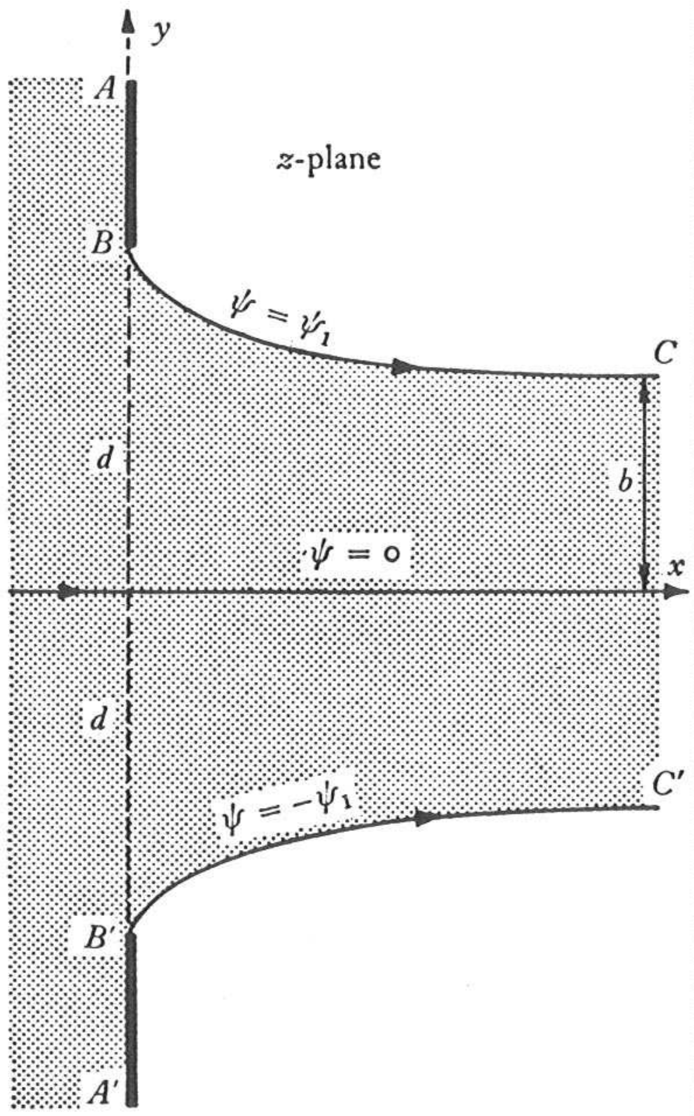
2-d potential flow (conservation of energy) $\Rightarrow$ analytic form:

$$x = \frac{2d}{\pi + 2}(\tanh^{-1}\cos\theta - \cos\theta), \qquad y = d - \frac{2d}{\pi + 2}(1 + \sin\theta),$$

$$\theta = \text{angle of streamline}, \qquad -\frac{\pi}{2} < \theta < 0.$$

90% of contraction occurs for $x < 0.8d$.

Good agreement between theory and experiment.

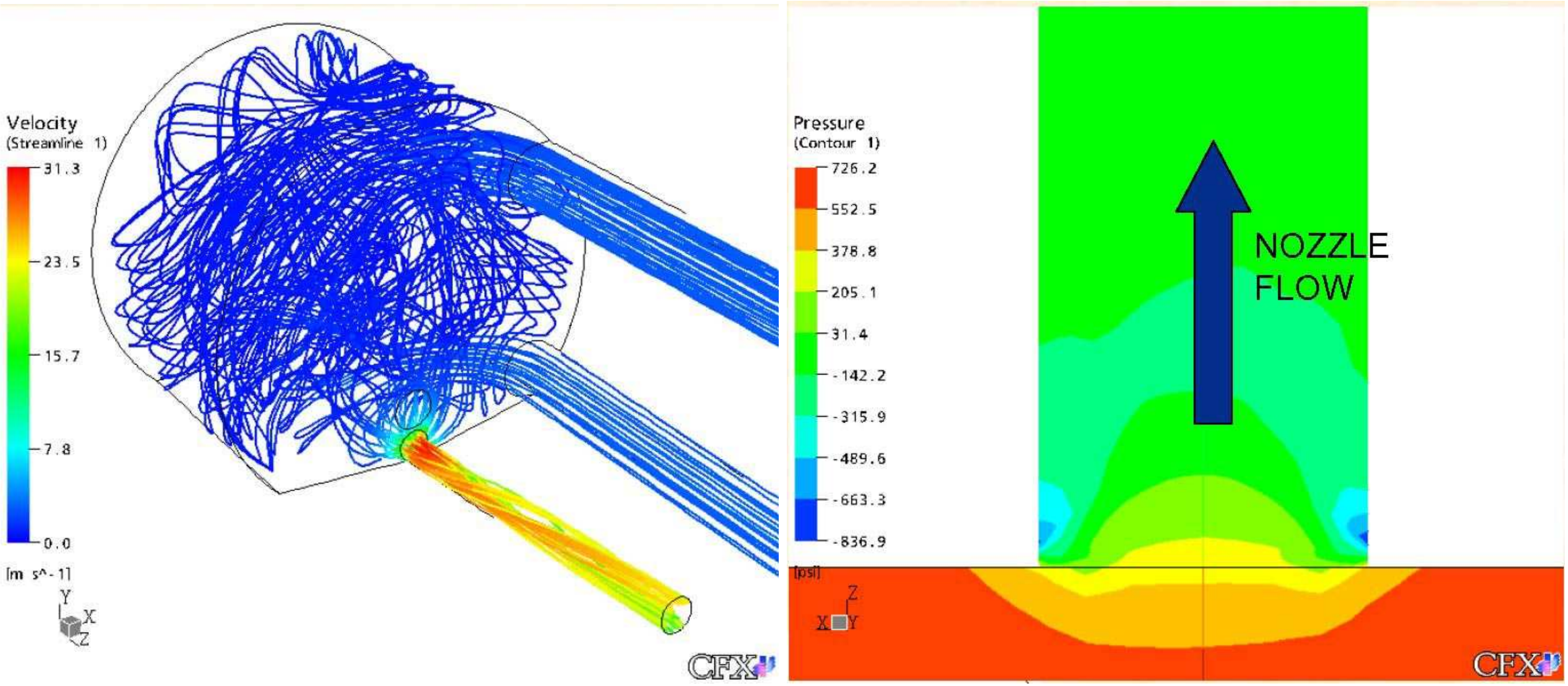


Dissipation and Cavitation Predicted by Fluid Dynamics Codes

(Mark Wendel, ORNL)

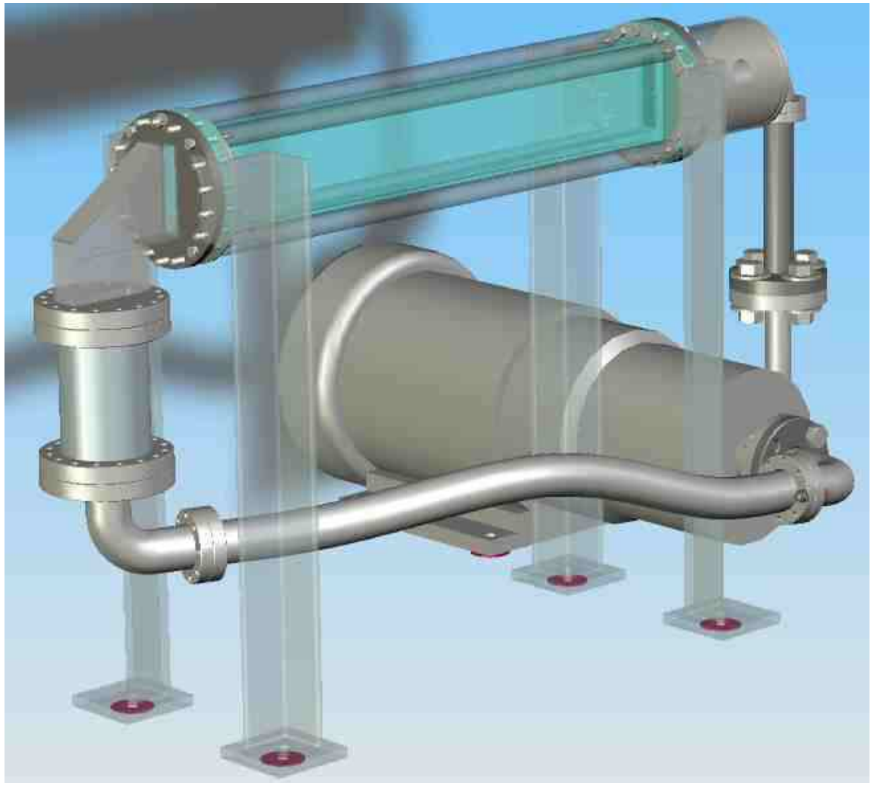
400 psi pressure drop predicted in vicinity of nozzle due to internal dissipation of energy.

Cavitation predicted at entrance to nozzle if hard edged.



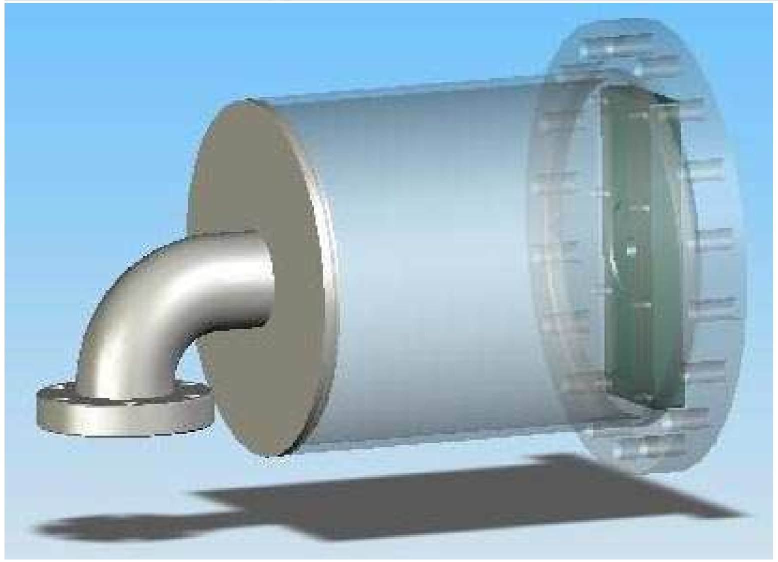
⇒ Should not use a sharp transition to a nozzle of nonzero length.

Nozzle Test Mercury Loop



Mercury loop with horizontal jet viewable for $30''$ in a Lexan channel.

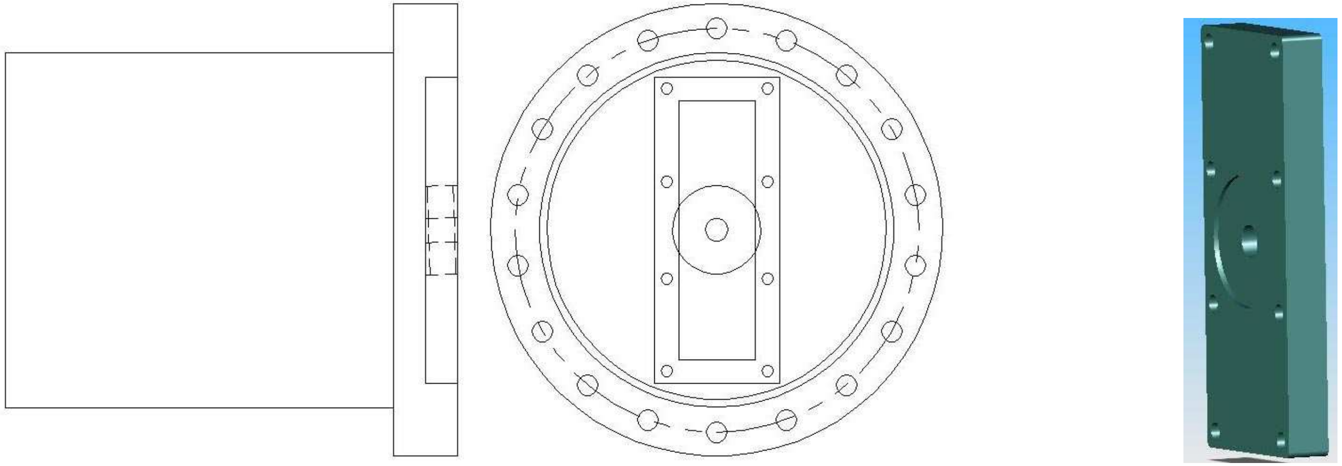
Lexan outer containment vessel sitting in a stainless-steel pan.



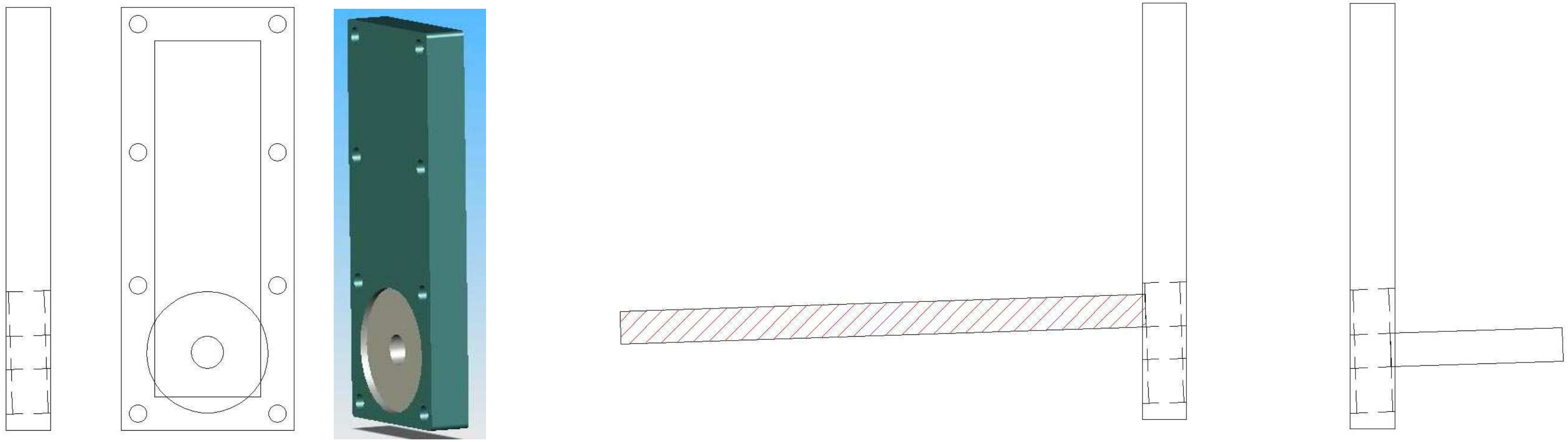
Mercury reservoir, $6''$ long, $5.5''$ diameter, with
replaceable nozzle plate.

Nozzle Plate

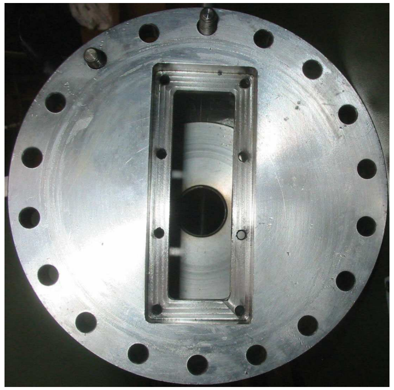
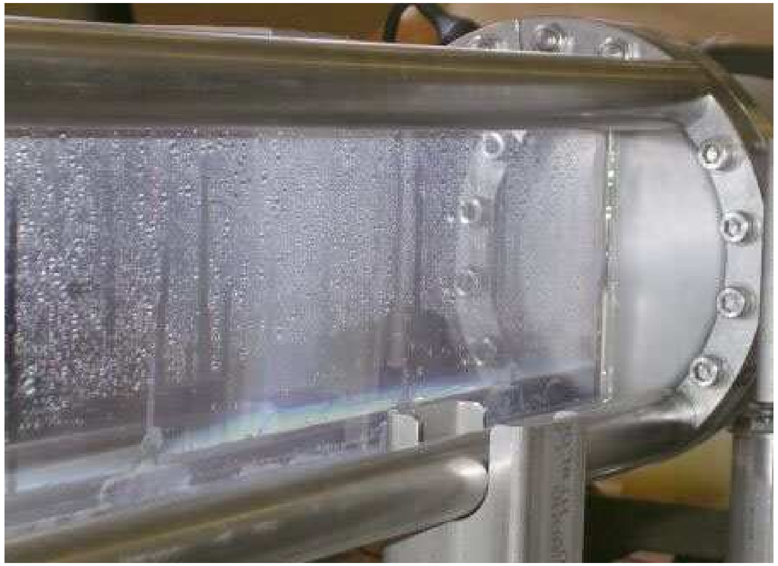
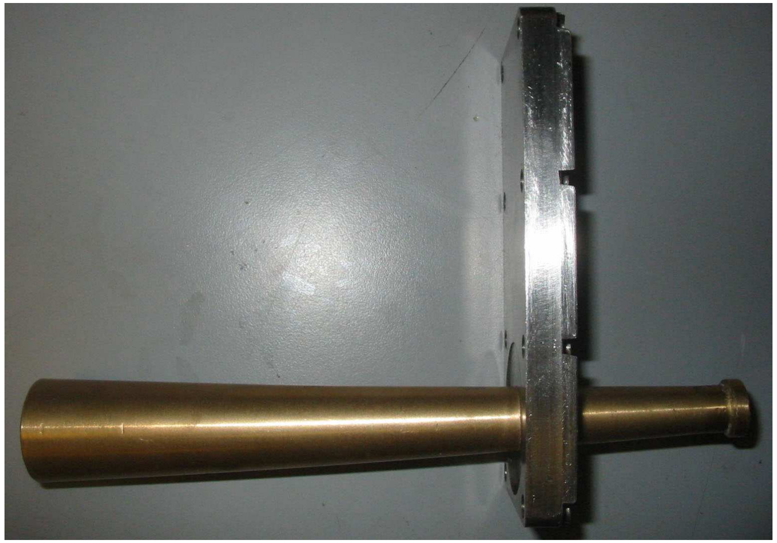
The aperture in the nozzle plate is tilted by 35 mrad with respect to the axis of the mercury reservoir.

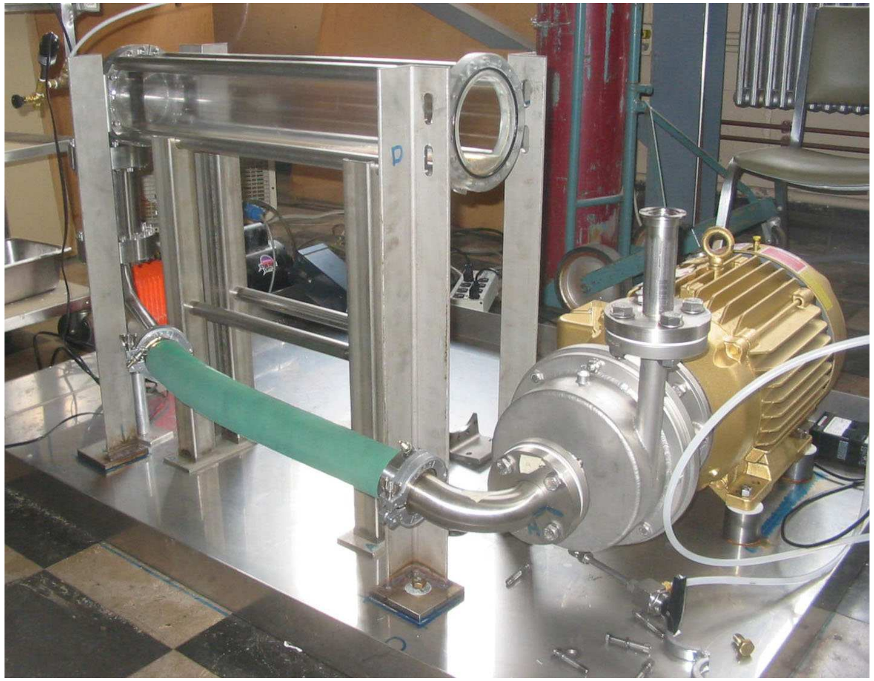


Nozzle plates will be built with the aperture offset from the center, with a dummy proton beam pipe, and/or a short tube-type nozzle.



Nozzle Test Components

Corcoran Centrifugal Pump

After a search for mercury-compatible commercial pumps that could meet the above requirements, we purchased a 4000 Series, Model D-DH2(AA) centrifugal pump from R.S. Corcoran, powered by a 20-hp, 480 V motor from Baldor.

R.S. CORCORAN Co.

MANUFACTURERS: • CORROSION-RESISTANT CENTRIFUGAL PUMPS • EXOTIC ALLOYED CHEMICAL PUMPS

500 NORTH VINE STREET
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TOLL FREE 1-(800)-637-1067
FAX (815)-485-5840

www.corcoranpumps.com • email: corcorpump@earthlink.net

PUMP QUOTATION

Date: APRIL 17, 2003
RSCQ #: J03041704

Attention: E. DE HAAS

c/o: PRINCETON UNIVERSITY

Pumping Application 25 GPM at 71 FT TH: Hg (1.56 L/S @ 420 PSI)
SOLUTION OF MERCURY, TEMP. 20-80°C, SPEC. GRAVITY 13.6

Pump **4000** **Series, Model: D-HD2 (AA)**
Description: CLOSE-COUPLED, HEAVY-DUTY DESIGN, CENTRIFUGAL
Mat'l of Const. (All wetted parts): STAINLESS STEEL
Suction: 1 1/2" RF FLANGE (150#) Discharge: 1" RF FLANGE (300#)
Mechanical Seal: Type 6006-8B1-40V Size 2.125
Rotating face CARBON (BALANCED) Elastomer VITON
Stationary face SILICON CARBIDE Metal parts 316 S/S
Motor: 20 HP 1765 RPM 480 Volts AC 3 Ph 60 HZ
TEFC - PREM. EFFICIENT Enclosure 1.15 SF 256TC Frame
Quantity: 1 **Unit Net Cost: $ 4952**
Shipping: 3-4 WEEKS FOB: FACTORY Approx. Shipping Wt.: 375 LBS.

Notes:
1. REFERENCE CURVE NO. 4-1501-17.
2. REFERENCE BASIC DIMENSIONAL DRAWING.
3. REFERENCE MOTOR DATA.
4. RECOMMEND SLOW START USING VFD CONTROLLER (NOT SUPPLIED BY CORCORAN).
5. **OPTION**: VFD MOTOR, 5000 RPM MAX., **NET PRICE ADDER = $572.**

Joel Kramer

FASTVISION

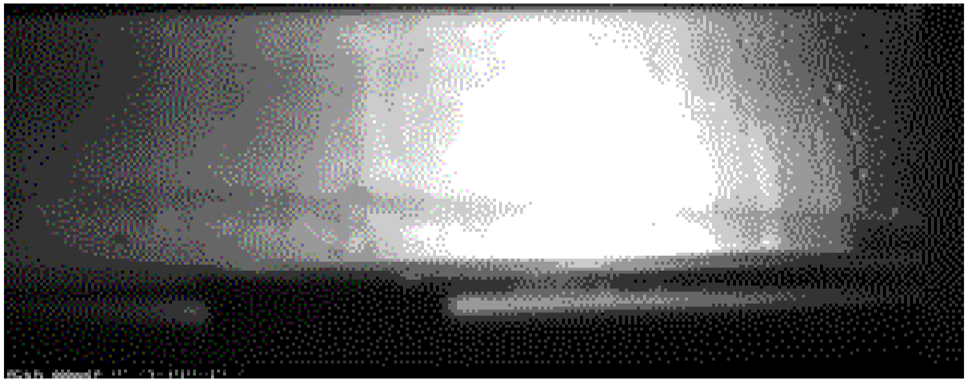
FastCamera13

- Uses Micron Imaging's MI-MV13 sensor.
- 1280 x 1024 x 8 bits.
- 15.36 mm $\times$ 12.29 mm active area.
- 12-μm square active pixels.
- 40% Fill Factor.
- 100 rows in frame: 5,000 frames/sec.
- 256 rows in frame: 2,000 frames/sec.
- 512 rows in frame: 1,000 frames/sec.
- 1,024 rows in frame: 500 frames/sec.
- Fast trigger via TTL signal.
- Onboard memory of 512 MB, $\Rightarrow \approx$ 400 full frames.
- Cost = \$8k.
- USB2.0 readout to PC.

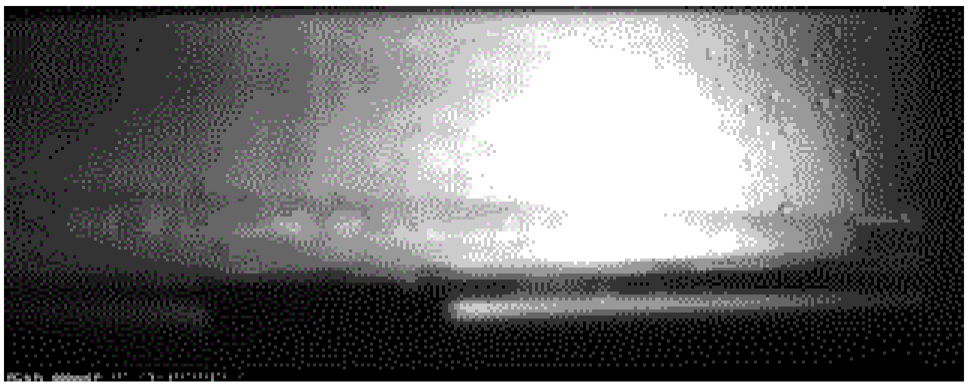
waterjet at varies pump speeds

6^{th},7^{th}, & 8^{th} runs @ 9:14 to 9:24 am

Frame rate: 1000 frame/sec (1 ms per frame)
1280x500 pixels, exposure time 0.25 ms
20 frames of video

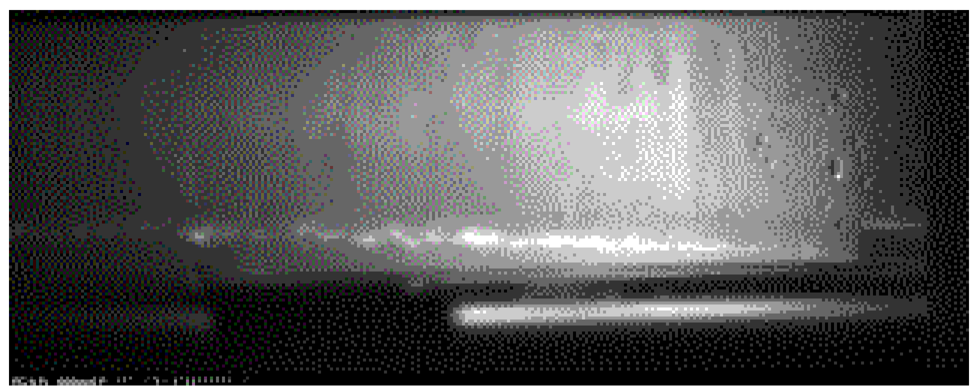


full speed



75% speed

50% speed



22 cm

waterjet velocity
~10, 12, & 7 meter/sec, respectively

Lessons So Far (from Water Jets)

- Can make jets of $v = 12$ m/s with present setup.
- Jet quality is good (but should be better).
- Have tested “no nozzle” and “mini-firehose” nozzle.
- Original rectangular viewing region did not hold vacuum,
  $\Rightarrow$ Replace with cylindrical viewing region.
- Air trapped is trapped in plenum,
  $\Rightarrow$ Operate at vacuum, or use small “bleeder” port at top of plenum.
- Corrugated flexible hose leads to cavitation in return line,
  $\Rightarrow$ Replace by smooth, flexible hose.

Next Steps

- Repeat measurements with improved plumbing.
- Study effects of gas pressure.
- Study configuration without plenum.
- Switch to mercury to confirm performance of best nozzle.