FOCUSING OF MASKLESS ABRASIVE JETS

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Abstract

Abrasive jets offer an economical alternative to benchmark micromachining technologies, but there is a need to develop a technique to focus abrasive air jets so that a mask (stencil) is not needed to achieve the required resolution. The poor resolution of maskless air jets is likely the result of internal nozzle roughness. By extrapolating from the literature, it was concluded that aerodynamic lenses and converging capillary focusing methods cannot be expected to be effective because the particles used in abrasive jetting are too large and the flows too turbulent. Focusing using eddy-current repulsion, electrostatic repulsion and diamagnetic repulsion were not deemed to be promising because none of the technologies examined could generate, under practical configurations, the required magnitude of force. Therefore, no technique for reliably focusing an abrasive jet was found. Since abrasive water jets have been shown to operate with very small divergence, a prototype abrasive suspension jet was designed, built and put through basic tests of functionality. The jet was easily capable of etching borosilicate glass with a driving (air) pressure of 6MPa and 12MPa, with apparently small dispersion. However, the mixing mechanism did not achieve a homogeneous concentration of abrasive during jetting, so was not capable of etching prismatic channels. Design improvements and future experiments were suggested.
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1. Introduction

1.1. Background

One of the primary fields of interest at the erosion laboratory operating jointly between Prof. M. Papini of Ryerson University and Prof. J. Spelt of the University of Toronto at the initiation of this work, was abrasive air jet machining. While very effective at many tasks, the wide dispersion of the abrasives in air meant that the only way to use the existing apparatus to etch micrometer-scale details for microfluidic applications, was to first machine a steel stencil, or mask. This mask can be placed over the target substrate and block the abrasive particles wherever etching isn’t supposed to occur. Designing and machining this mask for each new microfluidic network is a non-trivial cost and effort.

The purpose of this work was to answer the question whether abrasive jets can be somehow “focused” to achieve micrometer resolution without the use of masks.

1.2. Scope

This report contains three main sections. This introduction briefly reviews the concept of microfluidics, and looks at several technologies that currently exist to manufacture microfluidic networks in glass and biocompatible polymers. Section 2 looks at the causes of divergence in abrasive air jets, and then evaluates several concepts for the purposes of focusing abrasive jets. The most promising “way forward” is chosen: abrasive slurry jetting. The last two sections discuss the
detailed design of the laboratory’s prototype abrasive slurry jet, and the subsequent testing of the device. Finally, future design improvements and experiments are proposed.

1.3. Microfluidics

Lab-on-a-chip (LOC) technologies are being developed for a variety of uses, but very notably, are being developed world wide to detect disease biomarkers, i.e. by detecting the presence and concentrations of combinations of proteins, nucleic acids and cells that are correlated with certain diseases. Portability, disposability, ability to use small volumes of test fluids, and short diffusion paths leading to shorter assay times make the concept of LOC devices attractive, especially where there are few centralized test facilities (Chin, Linder & Sia, 2007).

A LOC consists of a microscopic network of channels and chambers. The chip material is usually a biocompatible polymer or glass. The scale of details of useful devices is comparable to the size of an animal cell, or about 30μm. This size scale needs to be taken into account whenever evaluating fabrication technologies for microfluidic applications.

1.4. Technologies for Machining Microfluidic Networks

1.4.1. Benchmark Micromachining Technology - Lithography

The dominant technology used for fabrication of microfluidic devices is lithography, literally “writing on stone” in Greek. Generally, this group of techniques consists of creating a mask with the required pattern, transferring this
pattern onto the substrate, and then etching the substrate along the transferred pattern.

The widely used subtype is photolithography, and consists of creating a master mask that has the negative or positive of the microfluidic network pattern, then placing the mask over a photoresist-covered substrate, and using UV radiation to either help remove or to help harden the exposed photoresist, depending on the chosen chemistry of the photoresist and the developer fluid. The substrate is etched where it is not protected by the photoresist, by either a wet or dry method. Photolithography can achieve detail resolution of about 1μm (Roy, 2007), although smaller resolutions down to about 100nm have been reported in laboratories (discussed in Xia and Whitesides, 1998). Soft lithography is another commonly used subtype, and consists of using a master mould to create elastomer stamps, which are in turn used to mould prepolymer into the required microstructures at a resolution down to 30nm in a lab (discussed in Xia and Whitesides, 1998).

1.4.2. Laser

Laser Direct Imaging includes ablation of deposited films off of a substrate, curing or baking patterns of functional material onto a substrate (removing excess with a solvent), or growing structures electrochemically onto the surface (Roy, 2007). The technique can be used to create 3D features, which is not possible with standard lithography. The resolution of Laser Direct Imaging systems can be between 5-100μm, generally limited by laser wavelength, which in turn is limited by practical considerations such as overheating, safety and ability to drive the required chemical reactions (where acceptable wavelength may correspond with
absorption or excitation energies of the chemical involved). A second consideration of Laser Direct Imaging is that most lasers are Gaussian, and require optical alternation to achieve a uniform effect across the beam width. Lasers are similar to abrasive jets in the later respect (see Ghobeity, Krajac, Burzynski, Papini and Spelt, 2008, for example sections of channels cut by abrasive air jets).

1.4.3. Inkjet Printing

Inkjet printing can be use in microfabrication of 2 or 3 dimensional features as one of two subtypes. The first is continuous charge and deflect (CCD), in which ink is being dispensed continuously, broken apart into uniform droplets by capillary waves, then deflected by electric fields to either the required location for the pattern, or into a catcher. This type can achieve drop sizes on the substrate of about 50-500μm. The second subtype is drop on demand (DOD), in which microelectromechanical devices dispense droplets when commanded by the control program. Higher resolutions down to about 14μm can be achieved with DOD systems (Roy, 2007).

Inkjet technology can be used in conjunction with lithographic techniques (Roy, 2007). The inkjet head can print the etch-resist directly onto the substrate, eliminating the need to fabricate an expensive master mask.

Roy (2007) summarizes the challenges for microprinting with inkjet technology in the field of microfluidics. First, it is not suitable for viscous materials, such as polymers. Second, it was developed for use with paper, which is porous and absorbent. When used on non-absorbent substrates, the ink tends to spread and decrease the resolution. Thirdly, when particulate inks are used, the
system will tend to build non-uniform structures via the Marangoni effect, or
differential evaporation rates at the edges compared to the center.

1.4.4. Centrifugal and Cogwheel Acceleration

Poppe Blum and Henning (1997) developed a technique for
deagglomerating small particles in a vacuum, by feeding compressed powder
radially into a fast-spinning, toothed wheel. The wheel broke apart the
incoming powder into a spray of micron- and submicron particles in the
tangential direction of rotation. One could imagine that the device might
produce a dispersed jet from a compacted source of fine abrasive particles, at
the likely cost that the wheel would experience considerable erosion. Also, the
wide particle distribution in that study indicated a mask (stencil) would have
to be used, and a very large fraction of the particles would be wasted on
impacting the mask.

Deng, Bingley, Bradley and DeSilva (2008) built a centrifugal erosion test
rig in which particles are fed into the centre of a spinning disc, in which the they are
accelerated by centrifugal forces through ceramic tubes until they exit the disk.
Although the authors found that this technique gave good control over several
important erosion parameters, it produces a continuous spray of particles all around
the disk, rather than a jet. Using the centrifugal acceleration with a mask would be
exceptionally wasteful, and does not seem very useful for micromachining.
1.4.5. Micro-Milling

Jauregui, Siller, Rodriguez, and Elias-Zuniga (2009) used a 350µm diameter, 2-fluted end mill made of high speed steel, operating at 4000rpm at a feed rate of 10mm/min to cut channels in acrylic. Channel quality was compared with that of lithography of PDMS, masked abrasive air jetting of copper, and abrasive water jetting of aluminum. They found that the end mill could produce neat channel profiles and very comparable average surface roughness relative to lithography, and much better than those of the abrasive water jetting and masked “sandblast”.

Although economics were not discussed in detail, the authors did present that the micro end mill process was only marginally more expensive than both abrasive jet types, but much less expensive (one fifth) than lithography, so it was generally regarded as a good value. A brief internet search revealed smaller end mills are widely available with diameters down to about 0.005” (127µm) from McMaster-Carr and similar suppliers.

1.4.6. Abrasive Air Jets

Abrasive air jetting, or powder blasting consists of a jet of high-speed air with entrained abrasive media being swept over the substrate. This technology was only relatively recently been applied to microscopic scales by Slikkerveer (see 2000). The abrasive media erodes the surface to form holes, channels (Ghobeity, Getu, Krajac, Spelt, & Papini, 2007), or planar areas (Ghobiety, Papini, & Spelt, 2009; Ghobeity, Spelt, & Papini, 2008). When fine detail is required, an abrasion-resistant
mask (stencil) is machined for the given pattern, and is placed on the substrate to make the erosion by the jet preferential to the uncovered areas. Abrasive air jets can be characterized as having low capital as well as low operating costs, while maintaining high etch rates and a flexibility in type of operation; drilling, etching, planing (Ghobeity, Papini, & Spelt, 2009).

Ghobeity, Krajac, Burzynski, Papini and Spelt (2008) measured the velocity profile of their abrasive air jet of 25\(\mu\)m alumina particles operating with a driving pressure of 200kPa. The centerline velocity at the nozzle was 162m/s with a standard deviation of 18m/s, dropping linearly with the radial distance from the jet axis. The jet was firing into atmospheric air. Lemistre, Soulevant, Micheli and De (1999) built a novel sand-erosion test facility in which all the air was removed from the particle jet via vacuum before the particles impacted the target. The authors calculated a mean impact velocity of 163m/s for 80\(\mu\)m particles, 195m/s for 200\(\mu\)m particles and 153m/s for 600\(\mu\)m particles.

The resolution of masked abrasive air jet processes is presumably limited to the size of the largest particle in combination with the size of the hole or slot feature of the mask being used. A relatively “good” resolution for a masked abrasive air jet at the time of print was represented by a channel width of 300\(\mu\)m, with 30\(\mu\)m particles from a 180\(\mu\)m wide rectangular nozzle and at a stand off distance of 10mm (Qui, Wang, Wang and Song, 2009).

Without a mask the high dispersion of the jet after the nozzle exit lowers the resolution considerably. The dispersion in this discussion will be quantified by the half-angle of dispersion, defined in Deng, Bingley, Bradley and DeSilva (2008) as:
\[ \tan\left(\frac{\theta_d}{2}\right) = \frac{R_j - R_b}{X_d} \]

Where \( \theta/2 \) is the half angle of dispersion, \( R_j \) is the jet radius at the cross-section of interest (or equivalently, the scar radius on the target), \( R_b \) is the nozzle bore radius, and \( X_d \) is the stand off distance. Chevallier and Vannes (1995) state that a circular abrasive air jet will emerge from the nozzle in a cone with an apex angle of between 25-30 degrees, or about 12.5-15 half-angle of dispersion.

Qiu, Wang, Wang and Song (2009) reported the results of their unmasked abrasive air jet channels to compare with that of their masked channels, and show that with a 460\( \mu \)m diameter round nozzle, using 30\( \mu \)m diameter particles, driving pressure of 400kPa, at a stand off distance of 1mm, the scar diameter is probably (by inspection from their scaled photograph) just over 0.5mm. This translates into a divergence half-angle of on the order of 1 degree, which is relatively small. Interestingly, the authors noted that there were no unusual shielding, or “flux”, effects due to the very small stand off distance and rebounding particles interfering with the paths of incoming particles.

Deng, Bingley, Bradley and DeSilva (2008) were comparing the relative merits of gas-blast to centrifugal technologies in erosion testing, and observed half-angles of dispersion (or divergence) in excess of approximately 5 degrees from the nozzle for 75-150\( \mu \)m particles at a very slow speed of 16m/s. They found that dispersion angle increases linearly with speed, and decreases with particle size. Shipway and Hutchings (1993) observed what can be calculated as about 18 degrees half-angle of dispersion in their tests with a rough nozzle, and about 10 degrees with a smoother nozzle, using silica particles traveling at low speeds of
about 60m/s.

Besides divergence, abrasive air jets abrade the target area non-uniformly: according to Ghobeity, Krajac, Burzynski, Papini and Spelt (2008), the velocity of particles decreases linearly from the center axis of the jet, and the probability that a particle will strike at some radial position from the center of the jet can be characterized by a Weibull distribution. This results in an approximately Gaussian erosion profile because of the radially-varying particle kinetic energy. A major factor contributing to this profile is fluid friction with the nozzle capillary walls (McCarthy & Molloy, 1973).

This uneven distribution can be ameliorated by using a Laval-type nozzle, which ‘sandwiches’ a rectangular, particle-laden air jet between two pure air jets. Achtsnick, Geelhoed, Hoogstrate, & Karpuschewski (2005) used a 3mm long Laval nozzle to accelerate particles up to 290m/s, and at a visibly more uniform flux compared to a similarly-sized circular nozzle used as a control. A quick calculation revealed that the authors achieved a divergence half-angle of about 5 degrees with either nozzle. Interestingly, this nozzle contains a low-pressure region that enables vacuum feeding of the abrasive media.

Qui, Wang, Wang and Song (2009) also used a rectangular nozzle in part of that study, stating it had a more uniform flux. However, the authors preferred to use the rectangular nozzle for masked jetting only, and used a circular nozzle for unmasked etching. An unmasked rectangular nozzle might make machining smooth radii, such as microchannel elbows, more complicated.

A Wide dispersion means the current generation of maskless abrasive air jets
are generally not capable of machining at a resolution that is useful for microfluidics.

**1.4.7. Abrasive Water Jets**

Abrasive water jets are similar to abrasive air jets in that a pressurized fluid is used to accelerate an abrasive to high enough speeds to erode a substrate. The major difference between air and water jets, is that water has a much higher viscosity and achieves much lower Reynolds numbers for same dimensions and flow speed, thereby giving a more well-behaved flow. There are two major subtypes of abrasive water jet: entrainment-type and slurry-type.

**Entrainment-type Abrasive Jets**

An entrainment-type abrasive water jet, or abrasive water injection jet (Louis, Pude, von Rad, & Verseemann, 2007), consists of a highly pressurized fluid, 248-648 MPa (36-94 ksi) (Lorincz, 2009), passing into carefully designed mixing chamber / mixing tube (Hashish, 2006) where an abrasive-laden, pressurize air stream is injected and mixed with the water (Miller, 2004). This mixture of water, air and abrasive is then released through an abrasion resistant orifice made of ruby, sapphire or diamond (Hashish, 1996). 3D features have been demonstrated using angles cutting heads / nozzles with the correct degrees of freedom (Lorincz, 2009).

Steel, stainless steel, titanium and alloys of thicknesses 152-203mm (6-8”) are routinely through-cut using abrasive water jets. Some machines are able to cut 457-508mm (18-20”) thick alloy steel work pieces (Lorincz, 2009) The materials that high-pressure cutting is reportedly not useful for are: tempered glass, tungsten...
carbide, certain ceramics, diamond and composite materials, which can delaminate (Lorincz, 2009).

Kerf-widths (widths of cut) down to 300μm (Lorincz, 2009) or 200μm (American Society of Mechanical Engineers, August 2009) have been claimed by large commercial cutting operations. Commercial microcutting with orifice diameters of 76μm have been used in the literature (Hashish, 2006).

Hashish (2006) characterized the abrasive water jet-based cutting of packages for flash memory cards. He used a commercially-available 380μm diameter mixing tube at the “longest possible” length of ~63mm to achieve “as collimated flow as possible”. The orifice mount was diamond to resist fatigue, and the orifices used had diameters of 76μm, and 120μm, 127μm. The particles were 220 mesh (67μm diameter maximum) garnet, the pressures were all in the range 375-400MPa, and the stand-off distance was 1mm. One of the parameters examined was to observe the kerf width variation with respect to time. This table is shown as Figure 1. The kerf width was measured at the beginning of the trial as being approximately equal to the mixing tube diameter but smaller than the jet exit diameter. After about 30 hours of use, the mixing tube and orifice eroded at different rates, and the kerf width become larger than the jet exit diameter. Wear of the nozzle occurred linearly with time, and there was negligible divergence of the jet at the beginning of the trial.
Khan and Haque (2007) studied factors contributing to jet dispersion. In their study, width of cut on glass increased with the stand off distance and with increasing driving pressure in the range 69-345MPa (10-50ksi), but the degree to which divergence increased with these two factors was apparently dependent on the choice of particle. The three particles used were garnet, aluminum oxide and silicon carbide. The authors characterized these particles by relative hardness only (garnet being the softest, followed by aluminum oxide and silicon carbide), but made no mention of the shape/angularity and size of the particles used. For both correlation studies, the smallest absolute divergence and the smallest variation of divergence over the two factors was achieved by garnet. The smallest achieved width of cut was about 10x nozzle diameter, using a 0.1mm diameter nozzle, garnet particles, at a pressure less than 138MPa (20ksi), stand off distance less than 2mm. The reason given for garnet achieving lower divergence was that it is softer, so doesn’t retain its cutting edges after initial impact with the glass to the same degree as the other

Figure 1: Kerf Width and Mixing Tube Diameter Variation. Source: Hashish (2006).
two materials, so can’t perform secondary erosion away from the impact area and give the illusion of dispersion.

Entrainment type abrasive waterjets are inefficient, since particles are not entrained long enough in the water to reach their maximum potential speed. The machines transfer less than 3% of the machine’s consumed energy for abrasion (Miller, 2004). Also, entrainment-type abrasive water jet performance drops rapidly at nozzle diameters below 500μm and ceases to operate at jet diameters below 300μm (Miller, 2004), although this might be disputed by the work of Hashish in 2006.

Although entrainment-type abrasive water jets, are very powerful for through-cuts, they are not intuitively appropriate for lab-bench micromachining, since they require multiple, bulky, high-pressure pumps.

**Abrasive Slurry Jets**

The second subset abrasive water jet device is termed “abrasive slurry jet” or “abrasive suspension jet”. These devices operate at much lower pressures (Momber and Kovacevic, 1997), and consist of pushing premixed “slurries” or “suspensions” of water, abrasive media and sometimes polymer additives (Louis, Pude, von Rad, & Versemann, 2007) out through an abrasion-resistant nozzle.

Miller (2004) demonstrated an effective abrasive suspension waterjet, operating at 70MPa and with 40-60μm diameter nozzles. The nozzles were laser-drilled from diamond and silicon carbide. The largest particles used were 8μm in nominal diameter, and the smallest were 50nm in diameter, but with an unknown distribution. A schematic of the piping is shown in Figure 2. The flow controller
directed specific amounts of water (1) directly to the nozzle, and (2) to the back of the abrasive suspension container, in order to push the suspension into the water flowing toward the nozzle. Trials where done for through-cutting and through-drilling, but not in etching. One of the most interesting finds from this study was the idea that a nozzle bore diameter-to-particle-diameter ratio greater than 10, the performance decreases; this was explained as when particles becomes much smaller than the jet, they increasingly follow the water streamlines moving away from the impact site instead of directly impacting the target.

Miller (2004) also outlined some of the main considerations for the future design of abrasive jets for micromachining. First, nozzles down to 10\(\mu\)m can be drilled in diamond, but the field of micro-electro-mechanical systems (MEMS) manufacture might yield developments in the quality of smaller boring. At bore sizes less than 50\(\mu\)m “good housekeeping” might not be enough to prevent clogging and blockage, and the abrasive storage containers might have to be prepared in clean room environments.

Figure 2: Abrasive Suspension Jet by Miller (2004).

Nguyen, Shanmugam and Wang (2008) built an abrasive slurry jet device and studied factors contributing to jet breakup in air. They used a system in which
pressurized water pushes a piston, and the piston forces abrasive slurry through a nozzle. A schematic of their system is shown as Figure 3. They used nozzle diameters from 0.19-0.84mm, low driving pressures from 1-4MPa, abrasive particle concentrations 1% and 5%, alumina particle sizes 10, 15, 25µm, and used a long chain polymer additive, Ciba Magnafloc 333, in concentrations of 0.1-0.5% by mass. They found that using the polymer additive increases the coherent length (“compact zone”) of the jets, and that this improvement decreases with increased driving pressure. The authors noted that using the additive comes at an increased cost of material and complexity of disposal.

Authors in the same group (Wang, Nguyen & Pang, 2009) demonstrated microhole formation using their abrasive slurry jet device. They operated with a 200m diameter, 10mm long, stainless nozzle. The replaced the stainless nozzles every 360 seconds, presumably to reduce the effect of increasing the size with increasing nozzle size due to wear. The pressures used were 1-3 MPa (145-435 psi), and the particles used were aluminum oxide with average diameters of 10, 13,17m. Based on a short discussion in McCarthy and Molloy’s (1973) review of stability of
liquid jets nozzle design, the authors stated that due to the very small contraction ratio of nozzle diameter to the diameter of the holding tank, the jet diameter could be considered equal to that of the nozzle. This conclusion was based on the idea that the smaller the contraction ratio, the less the turbulence of the upstream flow is transferred to the jet (McCarthy & Molloy, 1973), but also when the capillary length reaches a certain size, the flow inside is fully developed and probably more well-behaved. On the other hand at that source pressure and with such a long, think passage for fluid flow, i.e. 0.2mm diameter to 10mm length, the resulted in a jet that was not effective at etching glass at the impact site, and eroded more material as it flowed away from the impact site than at the actual impact site. An iterative calculation, taking into account the source pressure and the friction loss inside the long capillary, yielded an estimate for the jet speed of about 50m/s, much lower than ~150m/s seen with dry abrasive air jet machining.

Abrasive slurry jets have been demonstrated at 70MPa for high-quality cutting, and at 3MPa for underpowered etching. A more optimal pressure for etching would logically fall in the range in-between. Slurry jets present an attractive alternative to abrasive air jets to the apparently low divergence.

1.4.8. Plain Water Jets

Pure-water jets at high pressures have been around since the 1970’s as industrial cutting tools for paper, plastic, cloth, leather, fiberglass, organic composites, and at pressures over 300MPa, aluminum, steel and titanium (Hashish 1996). Hashish (1996) demonstrated a 690MPa water jet cutting and etching apparatus with a laser-cut, diamond, 25μm diameter nozzle. The resulting jet was
coherent for 25.4mm from the orifice, at which point it began to diverge. The diameter of jet in the coherent region was 76-127µm, depending on pressure and stand-off distance. The author reports qualitatively, that a polymer additive to the plain waterjet resulted in a longer coherent region before the jet began to diverge. Also, the additive can increase performance at slightly lower pressures because the longer polymeric chains have more kinetic energy than water molecules, but reduces the incremental improvement to performance as pressure is increased, because it also retards droplet formation that is apparently important in pure water erosion.

More recently (2006), the same author tested the use of 379MPa plain water jets to cut plastic packaging for flash memory cards. Cuts were said to have a “consistently poor” edge and surface quality. Entraining pressurized air into the plain water jet produced high-speed droplets that improved quality somewhat, but results were “inconsistent”.

Super pressure water jets have the distinct advantage of avoid clogging at its nozzle because of a buildup of abrasive media, so the nozzle size (and therefore the jet diameter) is only limited by available and affordable manufacturing technologies. On the other hand, because plain water jets operate at such high pressures, they require high pressure pumps and intensifiers that make the physical apparatus less appropriate for table-top micromachining.
2. Improving the resolution of Abrasive Air Jets

2.1. Particle Behaviour in Fluid Streams

The dimensionless parameter that indicates particle behaviour with respect to the streamlines of a surrounding fluid is the momentum equilibrium number, interchangeably called the Stokes number, \( St \), defined as the ratio of the particle relaxation time \( \tau_p \) to the characteristic flow time scale \( \tau_f \), multiplied by a correction factor (Lee, Yi & Lee, 2003):

\[
\lambda = St = \frac{\tau_p C}{\tau_f} = \frac{\rho_p d_p^2 U_f C}{18 \mu_f L_c}
\]

Where \( \rho_p \) is the density of the particle, \( d_p \) is the diameter of the particle, \( U_f \) is the mean fluid speed, \( \mu_f \) is the fluid viscosity and \( L_c \) is a characteristic length scale, and \( C \) is a correction factor. Sometimes, the above definitions above are given in terms of particle radius instead of diameters along with corresponding constants, as in Akhatov, Hoey, Swenson, and Schulz (2008). The reader should be aware that some authors use nozzle exit radius as the characteristic length \( L_c \), while others, such as Zhang et al. (2002), use nozzle diameter as the characteristic length scale. Therefore reader should be aware that a factor 0.5 discrepancy of particle Stokes numbers may exist when comparing results of different works.

The coefficient \( C \) is determined by one of several available formulae. For creeping flow, the correction factor is equal to 1 (Humphrey, 1990). A more empirical formula presented by Mallina et al. in 2000 (cited in Middha & Wexler, 2003):
Another formula for the Stokes correction factor $C$ was used by Wang and McMurry (2006):

$$C = 1 + 1.657 Kn_p = 1.657 \frac{2 \lambda'}{d_p}$$

where $\lambda' = 0.175 \frac{T}{P}$ is the mean free path in the fluid.

$$Knp = 2 \lambda' d_p$$

Where for both equations $Kn_p$ is known as the particle Knudsen number, $\lambda'$ is the mean free path in $\mu$m, $d_p$ is the particle diameter and $T$, $P$ are the absolute temperature (in degrees Kelvin) and pressure (in torr) respectively. The mean free path can be calculated as being about 69nm at 300K and 760torr ambient pressure. This gives a particle Knudsen number of about 5530, and a correction factor $C = 1.01$ using either of the latter two equations, for a particle with diameter 25$\mu$m.

The flow Knudsen number, $Kn$, differentiates between conventional continuum flow and free molecule flow. When calculated for an air flow but using the diameter 100$\mu$m nozzle, $Kn \approx 7 \times 10^{-4} << 0.1$ used by Wang and McMurry (2006) as a safe upper limited for conventional continuum flow, rather than free molecular flow. Therefore an abrasive air jet operates as a continuous stream.

For Stokes numbers less than 1, the streamlines follow the streamlines closely. For Stokes number greater than 1, the particle will move independently of the streamlines. This is shown schematically in Figure 4.
Figure 4: Particle Equilibrium Number and Streamlines

For applications of 25µm aluminum oxide particles (3700kg/m³) moving in air (viscosity is 1.983x10⁻⁵kg/m·s) from a 200µm nozzle, at an average speed of 150m/s will yield an uncorrected Stokes number of about 4000, which is much greater than the usual threshold of 1, clearly indicating that the particles are too big and heavy to be affected by diverging streamlines as the jet impacts the target sample. A Stokes number corrected by the factor C in the above equations, assuming ambient temperature and pressure, are estimated to be even higher.

This conclusion has the important implication that the extra cost and effort of evacuating air, as was done by Lemistre, Soulevant, Micheli, and De (1999), among others, would not be expected to reduce the dispersion angle of a jet of 25µm particles in air. The high equilibrium number also influences the usefulness of a number of aerodynamic techniques discussed in the following sections.

2.2. Causes of Divergence in Abrasive Air Jets

Shipway and Hutchings (1993) found that the divergence of a plume in an abrasive air jet is strongly dependent on (“among other factors”) nozzle bore
roughness and the nature of the particles. By inspection from their results, an increase in roughness ($R_a$) from 0.25$\mu$m to 0.94$\mu$m (280% increase) can increase the divergence (scar radius) by about 50% for round particles and about 40% for angular particles, given constant driving pressure and some constant stand off distance.

Shipway and Hutching followed soon in 1994 with a study in which they looked at the effects of increasing particle flux (done by using different sized glass spheres at different speeds) on the velocity of the particles in the jet, and on the effective scar radius. The spheres they were using were 63-75$\mu$m, 212-250$\mu$m, and 650-750$\mu$m lead glass spheres and 125-150$\mu$m soda lime spheres. The drawn stainless steel nozzle internal diameter was 4.72mm and the length was 308mm. The stand-off distance was 20mm. There was no effect of increasing particle flux on velocity within the range of flux used. However, for “higher” flux used, the authors observed and increasing trend that particles rebounding from the target could impact incoming particles, causing scattering and dramatically increased dispersion. The inter-particle interaction were not seen in the case where the target was removed, supporting the idea that rebounding particles can cause additional dispersion.

In a departmental study by Jason Liu in 2005 titled *Triboelectric Charging of AJM* (unpublished), the author worked out how much divergence can be expected in an abrasive air jet due to tribocharging. The conclusion was that the abrasive must acquire at least a million elementary charges each to have even a submillimeter effect on divergence, which itself was given as about 5mm.
2.3. Particle Size and Safety

It is reasonable to suggest that the smaller the particle, the better the best resolution of an abrasive jet. However there is a safety concern with using increasingly smaller particles. Chang (2010) summarizes that above 10µm aerodynamic diameters, airborne particles do not effectively penetrate into the lower respiratory system, while the opposite is true for particles with diameters less than 10µm. Particles less than 2.5µm are labeled “Ultra Fine Particles” (UFP’s), and along with nanoparticles (<100nm), have been linked to causing inflammation, impacting immune defense versus autoimmune, causing allergenic and neoplastic diseases, and causing cardio respiratory damage. Some main ideas discussed were that smaller particles not only penetrate deeper into the respiratory track, but also have a higher surface to volume ratio, thus allowing for a greater number of binding sites for bioactivation, and greater potential to disrupt physiological functions.

It is important to note that commercially-supplied abrasive particles of one nominal size contain some fraction of smaller particles, so that even if the nominal size is a “safe” size over 10µm, some fraction will be much smaller and toxic.

Thus there is ultimately a tradeoff between abrasive jet resolution and the level of safety measures that are required for operation that inevitably effect system and process cost.

2.4. Converging Capillary Focusing

Akhatov, Hoey, Swenson and Schulz (2008) demonstrated a converging capillary based particle beam focusing device, in which an airjet sheathed in an
annular flow of pure air, enters a ceramic “capillary” or tube, with a diameter that decreases very gradually. The authors listed the 7 main forces acting on particle in a fluid, eliminating all but two as negligible: Stokes forces, a viscous drag force, and Saffman force. The Saffman force is a steady shear force related to the transverse pressure gradient in a system where the velocity increases toward the centre axis of flow. This force pushes the particle toward the axis and was theorized as having potential to focus jets. The authors proposed that Saffman forces become important when the tube length is much greater than its inner radius. Starting with the formulas originally developed by Saffman (1965) and developed since, the authors developed an approximation for the threshold capillary length at which Saffman forces cannot be ignored.

The author’s capillary converged from 800 µm to 100, 150, or 200 µm, over a relatively long length of 19.05 mm. The particles used were very small: (diameter 0.21µm), and had an exit velocity of 100m/s, or about 2/3 the speed of conventional abrasive air jets. This resulted in a converging beam, and a focal point about 1mm from the nozzle exit, with a minimum observed diameter of about 3µm. The minimum beam diameter occurred for only about 100µm before very rapidly diverging. Continuously matching the stand off-distance depending on the depth of cut would add a considerable control complexity to the abrasive air jet system.

Also, the authors verified their theoretical pathfinding models for particles less than 1µm; and they theoretically extrapolated up to 1µm; if their trend continues, the focal point for abrasive particles about 25µm in diameters would occur before the fluid has even exited the nozzle. Thus, this technique does not look
promising, as presented, to improve resolution of practical abrasive air jet systems.

2.5. Coherent Particle Beams in Air

Gau, Shen and Wang (2009) studied rectangular microjets of widths 200, 100 and 50μm and found that a gas microjet breaks down (i.e. distance from nozzle to point of rapid expansion) much later than a “macro” size jet. This was explained by the absence of vortex effects, and a very different mixing process. In that paper, the authors present that at the microjet range of sizes, changes to the Reynolds number due to size of the jet nozzle alone did not affect the length at which the jet was stable: only changes in the Reynolds number due to changes in speed changed the breakdown length. This work was performed using a long, slowly-converging settling chamber made of Plexiglas that smoothed out the airflow that then exited through the rapidly-converging nozzle. The authors’ literature review revealed that circular nozzles break down more rapidly than do rectangular nozzles. Also, the maximum speed reported in the results is 50m/s, about a third of the nominal speed of abrasive air jets. For an abrasive air jet exiting at “only” 100m/s through a 100μm nozzle, the expected breakdown length using the formula from Gau, Shen and Wang (2009) is about 2mm; which is much less than the usual stand off distance of around 20mm, chosen to allow adequate acceleration of particles. The study did not look at the effects of including abrasive particles in the stream.

Shultz et al. (2010) designed a device for creating collimated particle beams to eventually be used for aerosol deposition of solutions in making printed circuit
boards. A gradually converging capillary focuses from an initially wide flow, annularly sheathed in air, taking advantage of radial Saffman forces for focusing over a very long capillary length. This was followed by a diverging and then re-converging capillary to eventually achieve a collimated beam. Having only the first converging capillary was shown to overfocus the flow rapidly after the nozzle exit. The improved design appeared to have several mm’s of stable beam length after the nozzle exit, at particle speeds of 100m/s and particle sizes <10\(\mu\)m. A schematic of calculated beam trajectories is given as Figure 5.

![Figure 5](image)

**Figure 5:** Theoretically calculated particle beam width flowing through a series of slowly converging and diverging microcapillaries by Shultz et al. (2010).

### 2.6. Aerodynamic Lens

The first aerodynamic lens system has been attributed to Liu, Ziemann, Kittelson, and McMurry (1995a, 1995b), and consisted of an aerosol of spherical particles with near unit density and size 25-250nm being drawn from atmospheric pressure in the sample container to a low-pressure container, through a series of orifices that progressively created a collimated aerosol beam. Before the particles
were released into the final chamber, they were accelerated through a nozzle.

Lee, Yi and Lee (2003) performed analysis and experimentation to determine the range of flow conditions and particle inertia’s in which a “beam” of particles could be generated using a single orifice (‘aerodynamic lens’) at atmospheric conditions. In general, using one orifice, particles converge rapidly, acquiring and axially-inward velocity component. After the orifice, the air streamlines diverge and exert a radially-outward drag force on the particles. Particles with a low inertia quickly diverge along with the streamlines, but particles with higher inertia continue to move radially inward. The authors stated that the challenge is to achieve flow and particle parameters in which the particles do not diverge, but also do not continue moving toward the axis so much that they cross the axis, and cause the beam to “over-focus”, or diverge after focusing. Orifice diameters of 2.5mm and 5.0mm were used with 1.0 and 2.5μm particles yielding Reynolds numbers in the laminar range 300-700. Flows with orifice Reynolds numbers 1-100 generally require very large particles to get a reasonable focus, which is not practical. Flows with Re over 700 get increasingly turbulent and cannot maintain coherent streamlines. Particles with Stokes number 0.1 followed streamlines closely, particles with Stokes number 1.0 created a coherent beam that remained focus for several orifice diameters, and particles with Stokes numbers 3.0 crossed the centerline and over-focused the beam. The conclusions from work was that particles can be focused effectively only in laminar flows, and only in the narrow range of Reynolds number 300–700, using micrometer – sized particles.

The problem above is that the given parameters tolerate impingement of
some particles onto the orifice surface, something that will lead to erosion damage when the particles are abrasive.

For the requirement for laminar flow, it is plausible to achieve Reynolds numbers less than 700 by using a 100μm orifice, and slower flows of about 100m/s at the orifice. There may be other practical barriers to achieving laminar flows in abrasive air jets, for example, if abrasive feeding mechanisms are based on oscillation of valves such as with MicroBlaser MB1005 by Comco Inc. The choice of using a smaller particles to reduce clogging at the nozzle would strongly be influenced by the willingness to handle particles that are increasingly dangerous to people (Chang, 2010).

Schreiner, Schild, Voigt and Mauersberger (1999) used two configurations of aerodynamic lenses in series to collimate laminar flows with low-Re (51~231). For the primary configuration, the authors used 5 different sizes of particles in the range 0.35~3μm particles with a driving pressure of 15-80torr into an evacuated (sub-torr) chamber. Higher pressures were said to translate into higher speed, turbulence and inability to collimate the flow. Pressures below 30torr did not exert enough force to focus the larger particles. They noted that non-spherical particles would broaden the beam by factors of about 2-4x.

Zhang et al. (2002) made a numerical model of a single lens particle beam focusing system in which creeping flows of Re = 12.5 was used to focus order of 1 μm and 0.1 μm in a vacuum, and verified their findings with data from literature. The authors noted significant impingement of the particles started at the minimum at Stokes number ~1, and recommended lens operation at St~0.2, at which
condition the focusing is close to maximum, but there is yet no impingement. They also noted that stepped nozzles helped to reduce divergence, and gravity might not be negligible (“marginal”) in their creeping system.

Wang and McMurry (2006) created a design tool for aerodynamic lens systems. From their literature survey they adopted an upper limit of laminar flow stability of only Re = 200, much lower than the upper limit of 700 calculated and observed by Lee, Yi and Lee (2003).

2.7. Jet of Individual Particles

The design concept here aims to ultimately fire individual particles in a coherent air jet. This essentially requires very rapid metering of particles into a moving laminar and fully coherent air jet.

Yang and Evans (2007) performed an extensive review of power conveying, metering and dispensing from bulk handling to precise and microscopic pharmaceutical and 3D printing applications. They looked at several groups of technologies including those based on pneumatic, volumetric, screw, electrostatic and vibration principles. They concluded that the most attention has lately been given to ultrasonic techniques. In their comparison and summary, ultrasonic dispensing/metering is able to produce one of the smallest doses of powder from the review technologies. The only other technology that achieves a smaller dose was the electrostatic-based xerography.

Although vibrations are generally known to increase the packing efficiency of dry powders by bringing particles into positions of lower gravitational potential, vibration-based methods use either longitudinal or transverse vibrations relative to
the dispensing capillary to break up inter-particle adhesion, thus breaking up agglomerates, and producing vacant sites to allow the particles to “flow”. The smallest cited dose by vibration was accomplished by Yang and Li (2003), at 10µg/s. Yang and Evans (2004) built a device that transferred vibrations from a sonogram through a water bath to a capillary wall that could meter individual doses of 50µg of tungsten carbide. A follow-up study on the similar design principal by Lu, Yang and Evans (2006) elucidated which design and operating parameters were fixed for resonance given a particular powder type and configuration, and which could be varied to change the dose mass. Some of the studied variables that influenced dose mass were: nozzle diameter, water depth, waveform, voltage amplitude, frequency and oscillation duration; but many of these were coupled

In the best case of ultrasonic feeding, Yang and Li (2003) achieved the given value of 10µg/s with 3µm particles of stainless steel (density of 8000kg/m³) and 50µm capillary nozzles. This amounts to a particle feeding rate of about 90 thousand particles per second. This might be a small mass, but nevertheless, these particles still have to be ordered into the jet one-by-one to complete this section’s design concept.

Flow cytometry is the group of technologies with which researches count and sort cells. A jet containing the fluid is hydro dynamically focused and broken into droplets by a nozzle, then electrostatically deflected to collecting bin. Counting is accomplished by a photodetector picking up signals from tagged cells passing by (Andersson & van den Berg, 2003). This technology is first attractive because typical cells are of the same scale as typical abrasive particles, i.e. red blood cells
have a disk diameter of about 6-8μm. However, flow cytometry uses a carrier fluid, the use of which would mean adopting a second phase in the air jets, or changing entirely to water jets.

Electrostatic xerography consists of tribocharging the particles, then attracting them to a selectively charged surface, and depositing to another charge surface. The authors of the review paper (Yang & Evans, 2007) comment that this method is not suitable for dense particles (the examples given were polymers) so might not be suitable for carrying dense particles usually used in abrasion.

Diamagnetic concentration (Peyman, Kwan, Margarson, Iles, & Pamme, 2009) was shown to be effective at focusing 10μm spherical polystyrene beads into a narrow file in a microcapillary, but this was necessarily done in a paramagnetic solution, and it is likely that higher-density abrasive particles would not flow freely in the stream, but sink to the bottom.

Optical tweezers are a technology in which a tightly focused laser is used to exert photonic forces on particles from 10nm to 100μm (Grier, 2003). A single laser exerts both a gradient force, that pulls an adjacent particle toward the axis of the beam, and a radiation pressure, which pushes the particle out along the axis of the beam. By controlling the laser’s focus and positioning, individual particles can be manipulated in three dimensions, even in the immediate presence of other particles (Grier, 2003). By using multiple lasers or arrays, multiple particles can be manipulated in complex patterns (Grier, 2003) either in fluid suspension or in the air (Omori, Kobayashi, and Suzuki, 1997; Knox et al., 2010). It seems plausibly to set up large arrays of optical traps (focal points) that “ratchet” particles from one
discrete potential well to one immediately adjacent in the direction of travel, rapidly and a large number of times, from some hopper or tray, up into the air and individually into a passage that leads toward an air jet. The particles would be entrained one-by-one, and the flow would be smoothed and focused in a long, slowly converging capillary. Although technically plausible, adding a very complex optical system to an abrasive jet feeding system would negate the main economic advantage that abrasive jet machining has over laser cutting.

Regardless of how particles are metered and feed one-by-one into some hopper, the particles would still have to be somehow injected or entrained into the fast-moving airstream that is just a couple of particle diameters in diameter. In this case, the design of the opening from the “hopper” into the airstream has to be design to allow only one-way movement of the jet, and in such a way that flow disturbances from the opening don’t make entrainment unfavourable. Eddies formed should not penetrate back into the particle feeding device. Smallest eddy size might be estimated with the Kolmogorov scale (Landahl & Mollo-Christensen, 1992) but only if a suitable steady-state power dissipation (W/kg) for the fluid can be first estimated.

At this time, there is no clear solution to the problem of how to order individual micro particles into a fast-moving air jet.

2.8. Estimate of Transverse Force Required for Focusing

Using some “typical” abrasive air jet parameters, it is possible to estimate what constant force a technique would have to exert over a whole flight path of each particle to correct the divergence. For the sake of argument, the objective will
be to correct the trajectory of a particle that is exiting from the nozzle 20 degrees
skew from its intended path, corresponding to an unfocused divergence of about
7mm on the target surface. The particle is 2700kg/m³ aluminum oxide, roughly
spherical with diameter 25µm, and has an axially velocity component of 150m/s
from a stand-off distance of 20mm. At this speed, the particle will reach its target in
about 133ms. The transverse force has only this amount of time to accelerate the
particle radially inward 7mm. Neglecting air resistance opposing the acceleration
for simplicity; we combine the Newton’s second law equation and the constant
acceleration equation rearranged for displacement:

\[ F = ma \]

\[ \Delta d = v_0 \Delta t + \frac{1}{2} a_0 \Delta t^2 \]

Resulting in an approximate formula for minimum force: \( F = m\Delta d/\Delta t^2 \) that yields a
minimum correcting force of about 7x10⁻⁵N.

**2.9. Diamagnetic and Ferromagnetic Focusing**

Whereas ferromagnetic and paramagnetic materials are strongly or
moderately attracted to magnetic fields, diamagnetic materials are weakly repelled
by them. The metric that describes both type and strength of magnetism is magnetic
susceptibility, written with a capital Greek letter \( \chi_m \). Magnetic susceptibility can be
dimensionless, or can be given per unit mass or per mole. Susceptibility is related to
relative permeability in the equation:

\[ \chi_m = K_m - 1 \]

Some reference values for \( \chi_m \) are: pure annealed iron, order(5000); FeO, 720x10⁻⁵;
Al, $2.2 \times 10^{-5}$; water, $-0.91 \times 10^{-5}$; diamond, $-2.1 \times 10^{-5}$; bismuth, $-16.6 \times 10^{-5}$, where a negative permeability denotes diamagnetism, a small positive denotes paramagnetism and a large positive denote ferromagnetism.

Since water is a diamagnet, organic tissue is repelled by magnetic fields. This was famously demonstrated by levitating a live frog in a very strong (16T) magnetic field, as discussed in Berry and Geim (1997).

Peyman, Kwan, Margarson, Iles, and Pamme (2009) demonstrated diamagnetic repulsion of 10µm polystyrene particles in a paramagnetic manganese solution. The authors demonstrated this in three different applications: focusing the particles into a narrow file inside a microfluidic capillary, trapping particles at a magnetic field set across a capillary, while letting fluid pass, and sorting particles by size into separate channels. The flow rate during focusing was 650µm/s, which is relatively fast for microfluidic applications but is negligibly slow relative to typical speeds (~150m/s) abrasive blasting. The authors gave the following equation for predicting the diamagnetic force on a particle:

$$F_{mag} = \frac{(X_p - X_m)}{\mu_0} V_p (B \cdot \nabla) B$$

Where $F_{mag}$ is the magnetic force; $X_p$ is the susceptibility of the particle; $X_m$ is the susceptibility of the medium, $\mu_0$ is the permeability of freespace ($4\pi \times 10^{-7}$ H/m), $V_p$ is the particle volume, and remainder are the flux density and the gradient of the magnetic field at the location of the particle.

The largest repulsive force observed by the authors on their 10µm particles was $1.2 \times 10^{-12}$N, and the author admits that the magnetic field and gradient values
were largely unknown (and not optimized).

Using the equation from Peyman, Kwan, Margarson, Iles, and Pamme (2009) it is possible to estimate a best case scenario and compare against the required force for re-focusing calculated earlier. This scenario assumes the jet is surrounded by an annular magnetic field to provide evening focusing from all axes.

First, bismouth is a metal and has the lowest susceptibility of natural materials, and so is the logical choice for a particles; 25μm in diameter. The susceptibility of air will be taken as zero (oxygen and nitrogen have negligible susceptibilities). The flux density will be generously taken as 1.2T, representing saturated iron. Ramadan and Poenar (2009) provide an achievable, but quite favourable magnetic gradient of 300T/m. This yields 4x10⁻¹⁰N, 100x better than what was achieve by Peyman et al., but much lower than the 7x10⁻⁵N calculated as being able to focus a fast-moving airstream. Note that Ramadan and Poenar themselves achieved forces of 10x10⁻⁸N on 1μm magnetic particle for the purposes of trapping, for which it was appropriate to have an iron pillar in the centre of their field giving them gradients up to 20T/mm.

The remaining 5 orders of magnitude of force can partly be achieved by using high-current, supercooled electromagnets, but the rapidly increasing capital and operations cost of the supermagnets would offset the economic advantage of abrasive air jets. Increasing the size of the particle would make a very large difference in the size of the force, but the larger the particle, the lower the best possible resolution of the system.

The other variable that would reduce the disparity is switching from a
diamagnetic to a ferromagnetic particle, which has susceptibilities larger in magnitude by several orders. The problem here is first of practicality: ferromagnetic particles will be attracted to a magnetic field, so that an annularly-created field would diverge the particle jet further. Therefore, the field would have to originate from along the whole axis of flight. Placing a micro-thin, magnetized iron wire in what is essentially the desired flight path of the jet would present an obstacle that the abrasive would tend to adhere to.

2.10. Eddy-Current Based Magnetic Focusing

Eddy-current separation is a technology that takes advantage of interactions between an externally-applied magnetic field and an induced magnetic field caused by eddy currents to create a force that can separate or sort conductive, nonferrous materials from (for example) waste streams (Lungu, 2009).

In the typical separation device (Rem, 1999), the dry material stream to be sorted is brought to the device via a conveyor belt. Underneath the end of the conveyor, there is a horizontal drum, covered with alternating poles of permanent magnets, rotating at many hundreds or thousands of rotations per minute. The changing magnetic field seen by the waste particles induces an eddy current in conducting pieces of waste; the eddy currents set up their own magnetic field, which is opposite to that of the drum and so repels the particle tangentially along the drum’s motion (Lungu, Rem, 2002).

Horizontal drum separation technology has the limit that it does a poor job separating out particles less than 5mm (Lungu, 2009). Certainly there has been some research in somewhat reducing this limitation (Lungu, 2009, 2005; Schlett
A concise guide to the governing equations was compiled by Rem (1999) for a drum with k poles and rotational frequency $\omega$, and particle backspin $\omega_p$. The assumption build into the following relationships is that the pole width is much greater than the particle size. Eddy currents created by a rotating drum in a conductive particle have a characteristic decay time (Rem, 1999, p. 21):

$$\tau = s'' \mu_0 \sigma R^2$$

Where $\tau$ is the eddy current decay time (s), $s''$ is an experimentally determined shape factor ($s'' \approx 0.1$ for sphere of radius $R$), $\mu_0$ is the permeability of freespace ($4\pi \times 10^{-7}$ H/m), $\sigma$ is conductivity (S/m), and $R$ is the some characteristic dimension of the particle (m). Effective separation is said to occur when the product $\tau \times \omega = \text{order}(1 \times 10^9)$. The separating tangential force is then (Rem, 1999, p.19):

$$F_{\text{tan}} = \frac{2 \pi s' B_a^2 V}{n \mu_0 w \left[ 1 + \left( \frac{\omega - \omega_p}{\tau} \right)^2 \right]}$$

Where $s'$ is a constant of order(1), $B_a$ is the applied magnetic flux density (T), and $w$ is the width of each pole pair (m). The tangential force can be expected to dominate over the normal (radial) force when (Rem 1999, p. 24):

$$s' \mu_0 (\omega - \omega_p) \sigma R^2 \ll 0.002$$

Where the symbols are the same as those defined earlier. The proposed design for an eddy-current based focusing device would work in the following way. Instead of rotating the magnetic field relative to the particle, a fast-moving, conducting particle (ideally aluminum) would be moving in the jet relative to an alternating
pattern of annular permanent magnets. The equivalent “angular speed” for a particle moving at speed $u$ (m/s) through a pattern of pole width $w/2$ (m) apart (Rem, 1999, p14):

$$\omega = \frac{2\pi v}{w}$$

For a pure aluminum ($37.8 \times 10^6$ S/m), spherical particle of diameter 25$\mu$m moving at 150m/s through some annual pattern of commercially available axially-magnetized permanent magnets (0.38T) of thickness of 0.001m and pole width 0.0005m, the tangential force is on the order of $3 \times 10^{-8}$N, short three orders from that which is required for useful focusing.

The force can obviously be improved by enlarging the particle and/or by using powerful electromagnets. However, using a larger particle with itself limit the resolution of the operation, while building electromagnets more powerful than a rare-earth magnet at sub-millimeter scales is a design challenge of its own.

### 2.11. Focusing charged particles with electric fields

The proposed focusing device here is to first statically charge the abrasive particles, then apply a magnetic field across the particle to induce a force on the particle. The familiar Lorentz force is governed by the vector equation:

$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$

Where $F$ is the electric force, $q$ the total charge of the point-mass (C), $v$ the velocity (m/s), and $B$ the magnetic flux density vector (T). Based on the previous force requirement for useful divergence of about $7 \times 10^{-5}$N on a particle over a stand-off distance of 20mm, it is possible to estimate the required charge per particle to make
this process feasible. If \( v \) is about 150m/s and \( B \) is 1.2T by saturating an iron core in an electromagnet, this yields a charge of \( 4 \times 10^{-7} \) Coloumbs, or trillions of elementary charges, per particle.

There are several ways of charging small particles, applied in electrostatic processes such as dust precipitation, electrostatic painting, (Dumitran, Blejan, Notingher, Samuila, & Dascalescu, 2008), inkjet printing (Yoshida, 2003). Some of the main techniques used for charging aerosol particles and droplets include: ion charging, induction charging, electrohydrodynamic spraying (“electrospraying”), contact charging and photocharging (summarized in Lackowski, Krupa & Jaworek, 2010). Photocharging or X-ray charging consists of dislodging electrons from material with incident electromagnetic radiation, but is useful for building only a couple of elementary charges per particle. Electrospraying and induction charging are convenient to use upon atomization of liquid droplets. In contact, or “tribo-“ charging, two materials of different work functions are brought into contact, and over some period of time, charge is transferred between media. Charging by ionic current in an electric field consists of either a direct current (DC) or alternating current (AC) electric field across the particles. Direct current devices are used when deposition on one of the electrodes is required, while AC devices are used when deposition is not permitted, such as in a potential abrasive air jet focusing device.

Lackowski, Adamiak, Jaworek and Krupa (2003) used an AC ionic charging devices to charge and collect dust particles from an oncoming air stream. The test particles magnesium oxide particles 10\( \mu \)m (nominal) in diameter. The authors reported a charge buildup of \( 5 \times 10^{-15} \)C per particle, or about 31 thousand elementary
A corona charging method (a type of ion charging) has one electrode that generates negative ions and passes them through the stream of target particles. A combined corona-electrostatic system, in which additional electrodes are used to increase the strength of the electric field to manipulated the particles, was modeled by Dumitran, Blejan, Notingher, Samuila, and Dascalescu (2008), in the context of a drum-type electrostatic separator. The authors present what they term to be a “crude” estimate of the actual charge of the granular particles being collected on the electrostatic drum; on the order of about $500 \times 10^{-12}$ C, or several billion elementary charges. However, this was estimated for relatively large particles with diameter 3 mm.

Matsusaka, Oki, and Masuda (2007) allowed 3.3 μm diameter, spherical alumina particles (density of 4000 kg/m$^3$) to impact-charge along the length of long pipes made of two types of stainless steel, aluminum, copper and brass. The charge polarity and magnitude was dependent on the material of the pipe, and the amount of charge was also dependent on the length of the pipe to exit. Since the charge of the substrate is equal in magnitude to the sum of the charges of the particles that impacted it, it was possible to measure the charge of each pipe at intervals and come up with an average specific charge per kg particle. The best, most stable charging was reported with 3 m long brass pipes, achieving an average charge of about four thousand elementary charges per particle.

To be useful in abrasive air micromachining, electrostatic focusing would need particles charged to a degree far above the apparent ability of the state of the
2.12. Conclusions on Focusing Abrasive Air Jets

Several focusing concepts were examined, and estimates were made of the magnitudes of forces that could be practically achieved for focusing. Unfortunately, none of the concepts discussed could exert a high enough force to achieve useful focusing. Abrasive slurry jetting was chosen for further work because of its apparently lower dispersion, combined with the fact that the lower pressures, compared to water abrasive injection jets, meant that a prototype would be comparatively easy and inexpensive to design and build.

3. Designing an Abrasive Slurry Jet

The objective was to design and build an economical and safe, maskless abrasive slurry jet (ASJ) that can etch glass at a resolution appropriate for creating microfluidic networks. The novelty of this work comes from the combination of intermediate pressure and requirement to etch, rather than cut, with microscopic resolution.

The terms abrasive slurry and abrasive suspension are used interchangeably, and both refer to an abrasive jet system where water and abrasive particles are premixed and accelerated together, rather than injecting particles into a moving water stream.

By intermediate pressure, it is meant a pressure that is high enough to accelerate the abrasive enough to cause useful amounts of erosion, but small
enough to be contained safely in off-the-shelf piping components.

The abrasive chosen was 25µm diameter alumina particles, characterized as sharp. This size was chosen because it was felt that the fraction of particles below the toxic limit, i.e. 10µm per Chan (2010), in the supplier’s containers with this nominal size.

The design of the lab’s first abrasive slurry jet prototype is presented in this section. A schematic of the concept is shown in Figure 6. All detailed drawings and parts bills may be found in the Appendix of this report. The whole jet was made for about CDN$4500, plus taxes and delivery.

![Figure 6: General Schematic of Abrasive Slurry Jet Prototype](image)

**3.1. Calculating Speed**

Whereas the operator varies the velocity only indirectly, by setting the pressure of an abrasive jet system, it is often of interest to be able to calculate the
speed of the jet. A rigorous analysis would consist of looking at the major and minor losses of the entire piping network. An estimate of the flow velocities in the piping network was done using the Bernoulli equation. The piping network consists of the:

1. tank of pressurized air
2. regulator
3. two tees with a purge valve and safety valve
4. hose
5. tee with a pressure gauge
6. quick disconnect assembly
7. sample cylinder

The air and slurry were assumed to form a smooth interface with no mixing or bubbling. See Figure 6. The water-abrasive mixture passes through the:

1. outage tube
2. nipple
3. pipe cap with micro-capillary (“nozzle”)

Because of its microscopic diameters, it was expected that capillary be the source of the greatest losses.

A reasonable first approach to solving the network was to perform an energy balance for the imaginary streamline passing from the water-air interface in-line with the axis of the slurry tank, out through the middle of the nozzle.

The gravitational potential and initial velocity due to mixing were neglected. The energy balance (in meters) and the final velocity were therefore:
\[ E_1 = E_2 \]
\[ E_1 = \frac{P_1}{\rho g} \]
\[ E_2 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + f \frac{L_{cap}}{D_{cap}} = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} \left( 1 + f \frac{L_{cap}}{D_{cap}} \right) \]
\[ V_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho (1 + f \frac{L_{cap}}{D_{cap}})}} \]

The prototype system limits were used for the first calculation. The inlet air pressure was set at 14MPa, the outlet air pressure was assumed atmospheric, the density of water taken as 998kg/m³, and the nozzle capillary dimensions were 152μm in diameter and 2.54mm in length. The average roughness of the inside of the EDM’s hole was assumed to be about 0.00163mm from a manufacturer’s website, giving a roughness ratio of \( r = \frac{1.63 \mu m}{152 \mu m} \sim 0.01 \) which was used on the Moody diagram. Plugging into the equation for final velocity (see above) and iterating in the normal manner results in:
\[
\begin{align*}
f &\approx 0.038 \\
V_2 &\approx 130 m/s
\end{align*}
\]
for 14MPa input pressure.

The remaining losses, whether major or minor vary as \( \sim V^2 \) at that fitting, and at any cross section within the water phase the volume flow rate is equal to the volume flow rate at the exit, denoted with subscript “2”: \( V_2A_2 = V_{cs}A_{cs} \) where \( A_{cs} \) and \( V_{cs} \) are the area of that cross section and the velocity at that section, respectively. If the smallest cross-section in the piping network before the nozzle is about 3.18mm (1/8”, i.e. the adaptor tube or the quick-disconnect stem), then the velocity of the fluid at that fitting is about 0.3m/s. If that size of fitting has a large major loss coefficient of 1.0, then it is responsible for a head loss of much less than
a meter, compared to the initial pressure head of 1491 m.

It can be shown that because the cross-sections of all the remaining fittings are so much larger than that of the nozzle, the local fluid speeds are much lower, and so the corresponding losses are negligible compared to the initial head and the losses at the nozzle. Therefore, a Bernoulli approximation of the velocity of a slurry jet need only include the initial and final static pressure terms, the final kinematic term, and the minor loss due to nozzle friction.

The velocity at 6 MPa can be calculated in the same way to yield about 80 m/s, rounded to one significant figure.

### 3.2. Required Velocity for Etching of Glass

The purpose of this section is to find estimates from the literature of what the minimum required speed is to erode glass. This requirement is especially important after the study by Wang, Nguyen and Pang (2009) in which the authors attempted to make holes in glass with alumina microparticles using 3 MPa driving pressure, but observed that secondary erosion around the targeted impact area on soda-lime glass removed far more materials than did primary erosion under the targeted circle. Assuming that the driving pressure and minor losses at the nozzle capillary dominate the Bernoulli energy balance, their maximum jet speed might be estimated at 50 m/s. The question becomes, between this speed of 50 m/s and the usual abrasive air jet speeds of 150 m/s or greater, what is the minimum speed that an abrasive slurry jet system should operate at for effective etching?

Knight, Swain, and Chaudri (1977) impacted 0.8-1.0 mm steel spheres at speeds of 20-300 m/s toward borosilicate and soda-lime glasses and examined the
fracture patterns, and compared them with those created by pointed and spherical indenters. One of their observations was that soda-lime and borosilicate glasses fracture differently. Borosilicate glass is affected by (Hertzian) cone cracks, followed by lateral and median cracks, followed by a reversal of the cone crack. Soda-lime glass sees splinter-cracks fanning out, followed by median and lateral cracks.

Weiderhorn and Lawn (1979) followed up soon after with a study to measure the relative three-point fracture resistance of glass subject to impact by 30-mesh (diameters < 590µm) SiC particles and 35 mesh glass beads. They found a noticeable drop in the fracture modulus (strength) of glass when the SiC particles were traveling at only 15m/s, indicating some initiation sites were formed and damage was done. Of course, 30-mesh includes a large proportion of particles much larger than those used in abrasive micromachining, so the low speed of degradation of the surface might not be directly comparable.

Leil, Camaratta and Digenova (1985) examined the impact fracture on tempered glass of helicopter windshields, developing their theoretical analysis based on Hertzian cone fracture, and Auerbach’s law, which is in turn based on the statistical likelihood of an impacting particle “finding” a flaw in the impacted surface. The authors concluded that sand or steel particles with radii less than 4mm moving at 80m/s will not cause unstable crack growth in typical tempered windshields. A rough estimate of threshold particle velocity using their model but with micrometer particles, an Auerback constant of $A=10.5e4$ (Fischer-Cripps, 2000, p.133), and excluding their specially-derived term for tempered properties,
yielded an unrealistically high threshold velocity. This results might have been, because under the Auerbach logic, micrometer particles are small and are unlikely to find existing cracks. This shortcoming of the Auerbach law, which predicts a linear relation between the indentor load required to initiate a Hertzian cone crack and the radius of a spherical indentor, is discussed by Fisher-Cripps and Collins (1994). They state that the law generally only applies to “well-abraded specimens”.

Yong and Kovacevic (1997) presented a theoretical development to quantify the role of abrasive / water film in sapping kinetic energy during super high pressure abrasive water jet cutting with mesh 60 (diameter < 250μm) garnet particles. In larger industrial processes, where a large quantity of fluid under tremendous pressure creates a thin film of water, broken abrasive dust and fragments form the target that sap some of the kinetic energy of the oncoming particles. Using their Hertz-based models, the authors presented that the minimum velocity of abrasive particles for effective cutting is 370-406m/s, and stated that this range was in agreement with the solution from momentum-based analyses from the literature.

Andrews and Kim (1999) shot ~mm sized glass beads at hard surfaces and recorded whether the bead fragmented or rebounded intact. There was considerable scatter in their data, although a very crude extrapolation from their results would place fragmentation of micrometer particles somewhere around 90m/s. It is unclear how the theoretical basis for surface fracture or particle fracture would differ.

Momber (2001) experimented on quasi-brittle materials (i.e. several formulations of concrete) to first find their compressive stress-strain curves, then
find the energy associated with fracture. He then found that the pressure of a water-driven particle erosion pressure (in the range 100-350MPa, using an entrainment-type abrasive water jet) could be related to the fracture energy from the stress-strain curve. The author suggested that the threshold pressure from the calculation could then be used to estimate the threshold velocity for fracture per the proportionality:

\[ V_{th} \propto \sqrt{P_{th}} \]

Unfortunately, the author did not calculate the threshold velocity in that paper.

Wensink and Elwenspoek (2002) attempted to quantify the transition point between ductile and brittle modes of erosion on borosilicate glass, soda-lime glass, and single-crystal silicon. They use a variety of speed and particle size combinations and calculated the kinetic energy of those impacts and the corresponding average erosion rate per particle. Their logarithmic graphs clearly show an increase in the erosion effectiveness of each particle at some ductile-to-brittle transition over a decade or so of kinetic energies, for each material.

Now to compare the threshold values from Wensink and Elwenspoek (2002) to the slurry jet results from Wang, Nguyen and Pang (2009). Wensink and Elwenspoek presented a threshold kinetic energy of 24.0nJ per particle on soda-lime glass to achieve the more effective brittle-mode erosion. Wang, Nguyen and Pang used 10, 13, and 17\( \mu \)m alumina particles with a density of 3600kg/m\(^3\). They presented a progression of hole profiles with the 13\( \mu \)m particles, which have a mass of 4.2x10\(^{-12}\)kg, and so would need a velocity of 107m/s to achieve the transition-point energy of 24nJ on soda lime glass, much more than the 50m/s that can be estimated for the maximum pressure (3MPa) with Pang’s device using the
Bernoulli equation. The 17μm particles would only need to be traveling at 89m/s, but still far more than the 50m/s estimate in their device. It is no wonder that Wang, Nguyen and Pang only observed secondary and ductile modes of erosion. It is also possible to estimate the required velocity for larger 25μm alumina particles to achieve brittle erosion: about 40m/s for soda-lime glass or 32m/s for borosilicate.

Slikkerveer, Bouten, and de Haas (2000) presented an estimate of the threshold kinetic energy for minimum apparent erosion with the equation:

\[
U_{th} = 23225 \frac{E^{3/2}K_{IC}^6}{H^{13/2}}
\]

Where \(E\) is Young’s modulus, \(K_{IC}\) is fracture toughness, and \(H\) is hardness in units of pressure. Using values for soda-lime glass from Wang, Nguyen and Pang (2009), \(E=70\)GPa, \(K_{IC}=0.75\)MPa.m^{0.5}, and \(H=5.5\)GPa, so the threshold energy is 37nJ, significantly greater than Wensink and Elwenspoek’s (2002) threshold energy for transition to brittle mode, and requiring 50m/s using 25μm alumina particles for minimum damage. This later relation appears to be too conservative for general application, as even Wang’s much smaller particles clearly damaged the glass at that speed.

A slurry jet using 25μm alumina particles should achieve average particle speeds of 50m/s, at the very least, although being able to achieve closer to 100m/s would allow for a range of particle materials and sizes. It is unclear how changing the carrying medium from air to water changes the velocity required to cause damage to a brittle target.
3.3. Design of Piping Network

The piping network in the slurry jet prototype is continuous and biphasic. Air is supplied at one end, and meets the slurry in a free interface: there is no piston between the air and slurry. The slurry is pushed out the microscopic nozzle hole by both the head at the slurry-water interface and more importantly, by the hydrostatic pressure of the air at the interface. The components of the piping network are as follows:

1. cylinder of pressurized air
2. regulator
3. tee with a safety pop-it valve
4. tee with a manual purge valve
5. hose
6. pressure gauge
7. quick-disconnect stem
8. quick-disconnect body
9. slurry tank / sample cylinder
10. outage tube
11. nipple
12. nozzle

All piping connections are ¼”NPT, sealed with yellow gas line tape. All taped NPT connections were tested for leaking by spreading dish detergent over the visible connection, releasing some small pressure into the line, and watching for bubbles.

The driving energy for the abrasive slurry jet was supplied by tank of
industrial air at 18MPa (2600psi). This pressure was chosen because (1) it is easily obtainable and economical, and (2) this supply pressure was calculated as being able to drive abrasive particles to speeds comparable to those of abrasive air jets. The rated pressure of all subsequent piping components was chosen to be 21MPa (3000psi) or greater.

The regulator chosen is capable of accepting the cylinder pressure, and being able to achieve a very high outlet pressure (17MPa or 2500psi, comparable to the source pressure of 18MPa or 2600psi), so that a maximum range of driving pressures could be achieved. The regulator was ordered with both an inlet and outlet gauge. The pressure gauge on the free end of the hose was meant to provide another level of safety: before the hose was disconnected from the slurry tank, the operator would see the reading on the pressure gauge and be able to decide, whether the line was purged and safe to disassemble. The quick-disconnects on the hose and slurry tank allowed for fast disassembly of those two parts each time the tank had to be refilled.

The slurry tank, or “double ended sample cylinder” per the vendor, had the following characteristics:

- A volume that encompassed enough slurry to provide reasonable cutting times, on the order of several minutes, therefore about a 1000mL was estimated as a comfortable target for about 4 minutes of blasting at our higher pressures, assuming negligible nozzle wear.
- An NPT connection at both ends.
- A smooth inlet and exit, so as not to provide places where abrasive particles
could accumulate.

- Pressure tolerance of 21MPa (3000psi) or higher.

Several suppliers were contacted for quotes regarding such a device. Surprisingly, double-ended vessels with adequate strength were found with only two companies: Matheson and Swagelok. A 500mL, with internal diameter of 4.8cm (1.90”) tank was the best choice from what was available, given the requirements.

At least one workable alternative was designed. A seamless stainless steel schedule 80 pipe, 7.5cm (2.5”) nominal diameter has a standard wall thickness of 0.71cm (0.28”), and can hold up to 23MPa (3360psi) internal pressure at a safety factor versus yield of 2.2. A 45.7cm (18”) length carries 1250mL (76.2in³), or enough slurry for 4.4 minutes of continuous blasting at a jet speed of 150m/s and a 200μm nozzle. The 7.5cm (2.5”) pipe would be threaded and mated with reducing couplings at both ends. The nozzle end would then be mated with a “swage” smooth flow reducing threaded nipple, then a male nipple, and finally a nozzle / drilled pipe cap. The cost of the pipe cap changes very significantly with the size of the cap, so additional reduction might be desirable. On the other hand, additional reducers, depending on internal details, can provide additional places for slurry to be trapped. The input end of the “cylinder” could be similarly reduced to a comfortable size to mate with a quick disconnect or JIC connection.

The reasons why it was decided to buy a commercial model instead of making one were: (1) to save on construction time; (2) to avoid building a pressure vessel and risking a potentially dangerous error in assembly.

The outage tube listed is a male NPT fitting with a tube that extends into the
cylinder. The idea is that the tube samples from deep within the turbulent cloud, so that the poorly-mixed slurry at the edge of cloud doesn’t proceed toward the nozzle directly. The hope was that the addition of the outage tube would reduce or prevent clogging.

The nozzle design chosen for the prototype was simply an off-the-shelf, high-pressure pipe cap made from stainless steel, with a hole drilled by electrical discharge machining (EDM) at the departmental machine shop. The capillary length was reduced by facing to reduce losses, while maintaining a high safety factor against shear yield of the pipe cap. The smallest hole that was possible at the department shop with a Sodick AD325L tool was 152\(\mu\)m. The internal surface finish was not quantified.

Since the safety factors of the pipe cap are so high, it is possible to improve the capillary design further by altering the capillary aspect ratio length/diameter. The lower this ratio, the higher the maximum speed attainable.

### 3.4. Design of Mixing Mechanism

To evaluate the need to mix the slurry while it is sitting in the holding tank, a series of simple experiments were performed.

In the first, aluminum oxide particles with a nominal size 25\(\mu\)m were sprinkled into a beaker of water, and the settling was timed. Greater than 99\% of the dust settled to the bottom of the beaker within a second of contact with the water. The remaining grey film at the surface of the water is though to be the smaller particles that are present in every distribution, resting on the surface; their
weight inadequate to overcome the surface tension. This established that the slurry would have to be stirred constantly. Some of the alternatives for mixing that were considered were:

- magnetic mixing
- through-wall agitators
- vibration

Through-wall agitators, or propellers mounted on long shafts that are inserted through bearing in the wall of the vessel, were not considered further because drilling would compromise the strength and safety of the pressurized sample cylinder. Magnetic stirring consists of a small permanent magnetic inside a container is rotated by an externally applied magnetic field. This later was chosen for further trials because of its unobtrusiveness and commercial availability of parts.

A cylindrical, PTFE-coated stir bar, 12mm long and 6mm diameter, and a magnetic mixing plate (Corning #PC-420, 60~1150rpm) were borrowed from a neighbouring lab, along with an Erlenmeyer flask with base dimension 12.5cm. A slurry of 35mL water and about 13g aluminum oxide was poured into the flask and the mixer activated. In this situation where the mixer was in the middle of a cylindrically-symmetric mixing volume, the system had no problem achieving a fully turbulent and apparently homogeneous mixture. The next step was to test the magnetic mixing through a stainless steel pressure vessel. The stir bar was dropped into a Matheson 12.4MPa (1800psi) double ended sample cylinder and was placed over the mixing plate. Three important trials and observations:
## Trial Configuration: Observations:

<table>
<thead>
<tr>
<th>Trial</th>
<th>Configuration:</th>
<th>Observations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sample cylinder placed horizontally on mixing plate. Center both stir bar and cylinder on mixing plate center.</td>
<td>Cylindrical stir bar rotates and bounces as surfaces forced up by curvature of cylinder.</td>
</tr>
<tr>
<td>2</td>
<td>Cylinder was horizontal, but raised slowly away from plate</td>
<td>At a separation distance between cylinder and plate of ~1cm, jumping no longer observed. Rod vibrates only.</td>
</tr>
<tr>
<td>3</td>
<td>Cylinder was placed horizontally on table, and mixing plate was turned upside-down over and on top of the cylinder.</td>
<td>No vibration or jumping.</td>
</tr>
</tbody>
</table>

Therefore, a magnetic stirring system would have to operate from below a stainless steel sample cylinder, and would have to be very close to the cylinder (several mm’s) to be as effective as possible.

A custom mixing plate was built using an iron magnet glued to the rotor of a computer fan inside a water-resistant plastic box, in series with a resistor to reduce the current to the fan, and supplied by an AC/DC voltage transformer. The maximum resistance for reliable startup was 80 Ohm, but this low resistance produced considerable heat in the circuit, and the high levels of vibration, so a second resistance setting of 200 Ohm was added for steady state operation. The circuit was controlled with a switch with three positions: opened, 80 Ohm, 200
Ohm. Polyurethane pads glued inside the plastic box, under the fan and its rubber, vibration-dampening “screws” serve to bring the magnet closer to the box lid, and to dampen vibrations.

Adopting magnetic mixing required an appropriate surface inside the slurry tank for the stirring rod. The neck of the slurry tank, where the slurry tank converged smoothly to the exit, was chosen as a ‘nest’ for the rod. In order to ensure that the rod stayed in this area, and didn’t interfere with the outage tube or displace along the length of the sample cylinder and out of the magnetic field of the mixing plate, it was necessary to limit the range of angles of the abrasive slurry tank to the range of about 15–45°.

The magnet was positioned by hand and ruler, then glued with a glue gun. This meant that the load was minutely eccentric, and produced visible vibration. To avoid disturbance of the microscopic abrasive jet, the whole mixer had to be mounted from a stand, separate from the structure holding of the abrasive jet. This holder stand was to provide rotational (pitch) and vertical freedom, but at the same time rigid positioning, to adapt the position of the mixer relative to the neck of the sample cylinder at different angles.

3.5. Design of Structure and Angle Governing

The requirements of the structure were:

- Rigid support of sample and slurry jet
- Variability of jet impingement angle from 30° to 90°
- All materials to resist corrosion in water.
The angle $30^\circ$ was chosen because it represents the angle best suited for ductile erosion, while $90^\circ$ was chosen because it represents the best angle for brittle erosion (Wensink & Elwenspoek, 2002).

The final design consisted of the slurry tank clamped laterally between two angles, and held axially by 4 large bolts that pass through the angles and provide the clamping force. Polyurethane pads on the bottom and sides of the tank increase friction, dampen vibrations and protect the tank from scratching and denting during assembly/disassembly. The angles are held along their full length by short bolts to an I-beam, which in turn, bolts to a large stainless steel strap hinge.

The angle could be varied in a discrete manner. A small hinge mounted to the underside of the I-beam holding the L-angles was bolted to a long bar that terminated with two custom-built angle brackets. One leg of each of these custom angle brackets had a hole through which passed a single large bolt that also passed through holes in vertical plates (rails), rigidly connected to the common baseplate. The position of the holes in the rails determined the angle of the whole slurry jet assembly.

All structural components were machined by the author from aluminum grade 6061-T6. Structural connections were all stainless steel hex bolts or flathead machine screws. The two hinges were bought off-the-shelf.

It should be noted that the structure of the abrasive slurry jet is somewhat overdesigned, and some savings might be made with additional optimization.
3.6. Design of Sample Mounting

The sample mounting assembly had these requirements:

- Rigid to resist vibrations.
- Some ability to change the stand-off distance between nozzle and sample.
- At least one direction of controlled motion, via linear stage.

Since the slurry jet had to be mounted on a moderate angle to accommodate positioning of the mixing rod, this meant that to achieve the 30° to 90° range, the stage had to be angled as well. Two angled verticals were designed for this purpose. One was designed to hold the stage at 45°, to be used with the jet at 45° for a 90° impingement angle. The second held the stage at 15°, to be used with the jet at 15° to achieve 30° impingement. Of course, an intermediate angle of 55° could also be achieved.

These angles verticals held a large plate, on which the linear stage was mounted transverse to the machine axis, which then held a large polycarbonate splash shield, and a rigid aluminum plate for mounting the sample. The sample was held to the plate by two aluminum strips each with two holes for the screws protruding from the plate. Wingnuts were used on the screws to put a clamping force on the strips, and therefore the sample. There was also a polyurethane pad between the sample and plate to increase friction.

The linear stage was sealed from the splashing slurry not only by the polycarbonate shield, but also by a large plastic bag, clamped between the shield and the sample mounting plate, and then below the base plate.
3.7. Design of Enclosure

The requirements of the enclosure were:

- Protection of the operator from splashing of abrasive slurry.
- Protection of operator from potentially lethal burst of pressurized components, and hose whip from a prematurely-disconnected quick disconnect.
- Containment of abrasive dust and water.
- Transparency for monitoring.

The front of the enclosure was made from a large piece of transparent polycarbonate. This front piece was extended at the top toward the back of the machine with an additional, but smaller piece, to strategically protect the operator from hose whip at the quick disconnect. The three remaining walls of the rectangular enclosure were just splash guards made from opaque, white polyethylene.

The base of the enclosure was just a sheet of aluminum with the edges bent up to form a large, shallow tray. A hole was punched at one corner for drainage.

4. Testing the Abrasive Slurry Jet Prototype

4.1. Test 1: High pressure and high particle concentration

Purpose:

The purpose of test 1 was to determine if the slurry jet could damage glass at its near-maximum pressure setting.
Table 1: Parameters of Test 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>12MPa</td>
</tr>
<tr>
<td>Particles</td>
<td>25μm sharp alumina</td>
</tr>
<tr>
<td>Slurry composition</td>
<td>5% alumina by weight</td>
</tr>
<tr>
<td>Nozzle capillary dimensions</td>
<td>152μm starting diameter x 2.54mm long</td>
</tr>
<tr>
<td>Magnetic mixer</td>
<td>on</td>
</tr>
<tr>
<td>Stand off distance</td>
<td>22mm</td>
</tr>
</tbody>
</table>

Procedure:

1. Add slurry through quick-disconnect body using funnel.
2. Rinse quick disconnect body.
3. Attach air hose via quick disconnect.
4. Fasten front shield onto angle brackets of enclosure’s side splash guards.
5. Turn on video camera.
6. Note whether or not water is dripping from nozzle.
7. Open valve from pressure cylinder to regulator. (valve from regulator to line is closed).
8. Set regulator to required pressure (regulator is still closed to line).
9. Open regulator to line and start timer.
10. After some interval, or when the slurry has run out, shut off main valve on air tank.
11. Purge line (1/4 turn).
13. Close regulator outlet to line valve.
14. Make observations of sample.
15. Disassemble nozzle from cylinder and examine nozzle hole.

**Observations:**

1. The outlet gage on the regulator did not reach the rated maximum outlet of the regulator.
2. The volume of slurry wasted because of the outage tube was \( \sim 20 \text{mL} \) (4% of total cylinder volume).
3. Losses during loading because of imperfect sizing of the funnel were responsible for a wastage of about 5% of the total slurry by mass.
4. There was negligible drip from the nozzle when no air was allowed into line behind the cylinder (i.e. line is closed).
5. At 12MPa and high particle concentration, splashing from sample was very significant. Heavy mist was observed to exit from the top of the enclosure. A camera outside of the enclosure was covered with water mist, but with no visible particles. The main valve was closed after only 38 seconds because of the perceived health risk if the mist contained fine particles.
6. There was massive fracturing at the impact area on the glass sample.
7. The scar size was much larger than initial nozzle size.
8. The nozzle eroded non-symmetrically, and the nominal exit hole diameter was several times that of the original. The accepted
explanation was that there was a partial clog that directed the jet preferentially to one side of the nozzle capillary. There may have also been a highly localized pressure buildup and burst.

9. The nozzle didn’t clog completely, but abrasive particles gathered just inside the nozzle inlet, after the adaptor tube.

Conclusions:

1. A slurry jet operating at 12MPa can easily etch borosilicate glass.

2. The configuration of the prototype, under the parameters of the experiment, may be prone to clogging.

4.2. Test 2: Inspect quality of mixing, no pressure

Purpose:

The purpose of the second test was to observe the quality of the mixing by the magnetic stir bar, using the slurry that was left over from the previous trial that was aborted before the whole slurry tank was used up.

Table 2: Parameters of Test 2

<table>
<thead>
<tr>
<th>Pressure</th>
<th>atmospheric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>25μm sharp alumina</td>
</tr>
<tr>
<td>Slurry composition</td>
<td>~5% alumina by weight</td>
</tr>
<tr>
<td>Nozzle capillary</td>
<td>N/A</td>
</tr>
<tr>
<td>capillary dimensions</td>
<td></td>
</tr>
<tr>
<td>Magnetic mixer</td>
<td>on</td>
</tr>
</tbody>
</table>

Procedure:

1. Turn magnetic mixer to steady state mode.
2. Insert battery-powered LED, on long wires, into one end of the tank.

3. Record observations from inside cylinder.

**Observations:**

1. Multiple, large ripples seen moving at surface of grey fluid.

2. Slurry surface just below entrance of outage tube, at 45 degree angle.

**Points for discussion arising from observations:**

1. What is the actual particle concentration of the exiting jet?

2. Is the non-symmetrical wear of the glass a result of the non-symmetric nozzle wear? Need to mark orientation of sample in relation to nozzle.


4. Is outage tube actually doing anything, if particles are gathering at nozzle exit?

**Conclusions:**

1. Magnetic stir rod was successful at creating a turbulent cloud of abrasive up to (at least) the vicinity of the entrance to the outage tube.

**4.3. Test 3: Etching with very dilute slurry and high pressure**

**Purpose:**

The purpose of the third experiment was to use very dilute slurry, relying on abrasive media accumulated in spaces within the nipple and outage tube from the
first test, to perform etching.

Table 3: Parameters of Test 3

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure</strong></td>
<td>11.75MPa</td>
</tr>
<tr>
<td><strong>Particles</strong></td>
<td>25μm sharp alumina</td>
</tr>
<tr>
<td><strong>Slurry composition</strong></td>
<td>&lt;5% alumina by weight: remainder from previous tests but add 500mL water.</td>
</tr>
<tr>
<td><strong>Nozzle capillary dimensions</strong></td>
<td>200um starting diameter x 2.54mm long</td>
</tr>
<tr>
<td><strong>Magnetic mixer</strong></td>
<td>off</td>
</tr>
<tr>
<td><strong>Stand off distance</strong></td>
<td>26mm</td>
</tr>
</tbody>
</table>

**Procedure:**

1. Add water to existing slurry already inside sample cylinder.
2. Rinse quick disconnect.
3. Attach air hose.
4. Place plastic sheet over top of enclosure to contain water mist observed in test 1.
5. Fasten front shield of enclosure onto angle brackets of enclosure’s side guards.
6. Turn on video camera.
7. Open valve from pressure cylinder to regulator.
8. Set regulator to required pressure (regulator is still closed to line at this point).
9. Open regulator to line and start timer.
10. After some interval, or when the suspension has run out, shut off main valve on cylinder.

11. Purge line (1/4 turn).


13. Close regulator outlet to line valve.

14. Make observations of sample.

15. Disassemble nozzle from cylinder and examine nozzle hole.

**Observations:**

1. The maximum outlet pressure attainable was 11.75MPa, even though the regulator inlet pressure was showing 18MPa (2600psi).

2. A small circular scar was observed in the borosilicate glass sample. The scar was “slightly larger” than 200μm, indicating some dispersion. The half angle of divergence was greater than 0.5 degrees.

3. There was minor wear at the entrance to the nozzle capillary.

4. The buildup of abrasive around the nozzle capillary inlet was still present after the run. It was not washed away or consumed during the jetting.

**Conclusions:**

1. An abrasive water jet at 11.75MPa will etch borosilicate glass with dilute abrasive.

2. The dispersion of the abrasive water jet was relatively small compared to that seen in abrasive air jetting.
4.4. Test 4: Feasibility of etching with pure water jet

Purpose:

The purpose of this test was to observe whether a pure water jet would show any signs of damaging borosilicate glass at its near-maximum pressure setting.

Table 4: Parameters of Test 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>11.5MPa</td>
</tr>
<tr>
<td>Particles</td>
<td>N/A</td>
</tr>
<tr>
<td>Slurry composition</td>
<td>pure water</td>
</tr>
<tr>
<td>Nozzle capillary dimensions</td>
<td>200μm starting diameter x 2.54mm long</td>
</tr>
<tr>
<td>Magnetic mixer</td>
<td>off</td>
</tr>
<tr>
<td>Stand off distance</td>
<td>22mm</td>
</tr>
</tbody>
</table>

Procedure:

1. Disassemble system, flush with water, reassemble.
2. Add 500mL water.
3. Attach air hose.
4. Fasten on shield.
5. Turn on camera.
6. Open valve from pressure cylinder to regulator.
7. Set regulator to required pressure (regulator is still closed to line at this point).
8. Open regulator to line and start timer.
9. When the water has run out, shut off the main valve on cylinder.
10. Purge line (1/4 turn).
12. Close regulator outlet to line valve.
13. Examine glass sample for damage.

Observations:

1. No trace of hole was observed after 38 seconds of blasting.
2. Roughening of large area on surface of glass sample was probably due to trace particles remaining in sample cylinder or capillary.

Conclusion:

1. A pure water jet will not etch glass at 11.5MPa from 22mm away.

4.5. Test 5: Homogeneity of slurry jet

Purpose:

The purpose of this test was to observe how the composition of the slurry jet compared with the original composition in the sample cylinder.

Table 5: Parameters of Test 5 - Constants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>6MPa</td>
</tr>
<tr>
<td>Particles</td>
<td>25(\mu)m sharp alumina</td>
</tr>
<tr>
<td>Slurry composition</td>
<td>2.5% alumina by mass</td>
</tr>
<tr>
<td>Nozzle capillary dimensions</td>
<td>152(\mu)m starting diameter x 2.54mm long</td>
</tr>
<tr>
<td>Magnetic mixer</td>
<td>VARIES</td>
</tr>
<tr>
<td>Stand off distance</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>
Table 6: Parameters of Test 5 - Variable

<table>
<thead>
<tr>
<th>Run</th>
<th>Mixer Status</th>
<th>Outage Tube Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>on</td>
<td>Installed</td>
</tr>
<tr>
<td>2</td>
<td>off</td>
<td>installed</td>
</tr>
<tr>
<td>3</td>
<td>on</td>
<td>removed</td>
</tr>
</tbody>
</table>

Procedure:

1. Measure 12.5g alumina powder, mix with 250mL water and pour through a funnel into the disconnected quick disconnect. A straw can be inserted alongside the funnel to help expel air.
2. Pour another 250mL water to flush rest of alumina from funnel.
3. Add stir rod.
4. Activate magnetic mixer IF required by special instructions for run.
5. Attach hose.
6. Place graduated cylinder in place of stage assembly to capture jetted slurry.
7. Set pressure to 6MPa.
8. Open pressure to cylinder / start stopwatch.
9. Replace graduated cylinder with a clean and empty graduated cylinder after every 40 seconds.
10. When the suspension has run out, shut off the main valve on cylinder.
11. Purge line (1/4 turn).
13. Close regulator outlet to line valve.

14. Measure alumina concentration in each of the graduated cylinders by measuring total mass of slurry in each cylinder, then removing the water from each cylinder to find the mass of the alumina. The difference is the mass of water.

15. Estimate wastage of abrasive media by totaling captured abrasive from the previous step, and subtracting from the 12.5g originally metered.

16. Repeat this procedure for each of the three runs, taking into account the special instructions.

**Results:**

1. Figure 7 shows that the concentration of the alumina was much higher in the first 40 seconds of jetting compared to the bulk slurry, and that the concentrations over the remaining intervals decreased with time and were much less than the original alumina concentration.

2. Table 7 shows that the mixer was predictably responsible for reducing waste, since without it, particles were unlikely to reach the entrance of the outage tube that extends into the cylinder 1.12in. Also, taking the tube out reduced waste further, since there were fewer crevices for particles to enter and be trapped in.
Table 7: Wasted Abrasive Media for Test 5

<table>
<thead>
<tr>
<th>Run</th>
<th>Wasted Alumina (%) of total in slurry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixer on, tube in</td>
<td>10%</td>
</tr>
<tr>
<td>Mixer off, tube in</td>
<td>86%</td>
</tr>
<tr>
<td>Mixer on, tube out</td>
<td>3%</td>
</tr>
</tbody>
</table>

Conclusions:

1. A mixing mechanism is essential for reducing waste of abrasive media.
2. The prototype’s mixing mechanism was not adequate for providing a homogeneous mixture. The vast majority of the abrasive was ejected in the first 0-80 seconds of jetting, leaving the remaining operation with miniscule alumina concentration.
3. The prototype was not suitable for making prismatic channels that
require a steady, homogeneous slurry jet.

5. Summary and Conclusions

5.1. Summary

- Abrasive air jets offer a relatively economical alternative to benchmark micromachining technologies, but rarely achieve resolutions fine enough for micromachining because of rapid dispersion after exiting the nozzle. A mask (stencil) is often used to compensate.
- The need for a mask might be eliminated by developing a focusing technique.
- The smaller the particles used, presumably the finer the resolution; however particles with diameters less than 10μm are toxic and require special safety precautions.
- Focusing an abrasive air jet with aerodynamic lenses or slowly-converging capillaries was not deemed to be promising, because abrasive air jets operate at in more turbulent regimes than the jets for which aerodynamic focusing has been demonstrated, and because 25μm alumina particles have too high an inertia to be manipulated by fluid forces in air.
- Focusing using an electric or magnetic external force was not deemed to be promising, because none of the technologies examined could generate, under practical configurations, the required minimum force for useful focusing. The main factors contributing to the small force were: a small volume, weak magnetic characteristic, or too small a surface charge.
• Since abrasive water jets generally have a much smaller dispersion compared to air jets, a prototype abrasive slurry jet was designed, built and put through basic tests of functionality.
• The design was based on pressurized air pushing directly on a free surface of a magnetically-mixed slurry of water and alumina particles.
• The jet was easily capable of etching borosilicate glass with a driving (air) pressure of both 12MPa and 6MPa.
• The mixing mechanism did not achieve homogeneity throughout the slurry-holding tank (sample cylinder), so the prototype was not capable of etching prismatic channels.
• The diameter of the abrasive slurry jet was comparable to that of the nozzle, indicating smaller dispersion compared to abrasive air jets, as required.

5.2. Future Design

In order to maintain a relatively constant jet diameter, it is recommended that future nozzles be made from drilled diamond, sapphire, ruby, silicon carbide, or another wear-resistant material. Miller (2004) reported that wear was not an issue during his trials when silicon carbide nozzles were used.

During several tests for homogeneity of the abrasive jet with respect to time, it was very obvious that most of the abrasive was released in the first 40 seconds or so of jetting, indicating that the mixing mechanism as-is provides insufficient mixing power to make the slurry in the tank homogeneous. The turbulent cloud remains in the bottom ~1/3 of the long sample cylinder. A new mixing mechanism
must be designed and installed if prismatic channels are to be etched.

The cylinder inlet should be redesigned to facilitate easier disassembly and reassembly, with a large diameter port for pouring in the slurry. This would work best in conjunction with a custom slurry tank made from schedule 80 pipe and a series of smooth flow reducers, discussed in section 3.3.

The stability and coherence of the abrasive suspension jet may be improved slightly by using a polymer additive at low concentrations (Nguyen, Shanmugam and Wang, 2008). This addition could realistically be expected to add on the order of several millimeters of coherent length to the jet, and would likely be useful where the stand off distance is larger than the stable region of the jet at the given driving pressure.

5.3. Recommended Experiments

The clear goal of future experiments will be to etch the smallest possible, even-profiled, and smooth-surfaced channels in glass, at the lowest pressure possible.

Experiments should be run to determine the optimal pressure to operate at. Pressure can be varied, while keeping stand off distance and feed rate constant, and measuring the channel profile. The optimal pressure will be the one at which there is negligible misting at the target area (relaxing the need for an air-tight enclosure), while being able to achieve the required channel depths at useful speeds.

In order to more accurately compare erosion rates and damage thresholds with the literature, the jet velocity values calculated with the Bernoulli equation should be verified empirically. Once experimental speed values are correlated with
input pressures, the calculation error in using Bernoulli assumptions can be
quantified, and the calculation adjusted accordingly.

A comparison between jet divergence of similar-sized alumina and garnet
particles should be done and compared with Khan and Haque’s (2007) finding that
using garnet in place of alumina will decrease dispersion. The two particle types
should be geometrically characterized and compared to decide whether it is the
shape, not the material that determines the degree of dispersion.

6. REFERENCES

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Roy, S. (2007). Fabrication of micro- and nano-structured materials using mask-


7. APPENDIX

This appendix contains the parts bills and drawings that were used to build an abrasive slurry jet prototype. Discussions of the design are given in the body of the above report.
## Project Cost Summary

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (CDN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piping</td>
<td>$1,556.48</td>
</tr>
<tr>
<td>Structure</td>
<td>$337.67</td>
</tr>
<tr>
<td>Stage Assembly</td>
<td>$2,073.88</td>
</tr>
<tr>
<td>Enclosure Assembly</td>
<td>$259.83</td>
</tr>
<tr>
<td>Magnetic Mixer Assembly</td>
<td>$94.67</td>
</tr>
<tr>
<td>Fasteners</td>
<td>$135.08</td>
</tr>
<tr>
<td>EDM Operation</td>
<td>$200.00</td>
</tr>
<tr>
<td><strong>Total Price:</strong></td>
<td><strong>$4,457.61</strong></td>
</tr>
</tbody>
</table>

**Notes:**
1. Prices do not include retail taxes or delivery fees.
2. Per-piece costs are given in preference to per-package costs.
3. Cost figures are meant to be a guide only; some figures are estimated or rounded.
<table>
<thead>
<tr>
<th>Line</th>
<th>Part name</th>
<th>Connections</th>
<th>Description</th>
<th>Buy from</th>
<th>Catalogue number</th>
<th>Price per unit ($CDN)</th>
<th>Quantity</th>
<th>Cost x QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pressurized air cylinder</td>
<td>590CJ female</td>
<td>T-size tank of industrial air. 2600psi. ask for factory-installation with regulator. assumed $12 delivery (not a firm quote)</td>
<td>Linde</td>
<td>-</td>
<td>22.91</td>
<td>1</td>
<td>22.91</td>
</tr>
<tr>
<td>2</td>
<td>590 CGA connection</td>
<td>590CJ male x 1/4&quot;NPT(M)</td>
<td>Brass connection.</td>
<td>Linde</td>
<td>-</td>
<td>20.00</td>
<td>1</td>
<td>20.00</td>
</tr>
<tr>
<td>3</td>
<td>Regulator</td>
<td>590CJ male inlet x 1/4&quot;NPT(M) outlet</td>
<td>single stage, high purity, high delivery pressure, max inlet = 3000psig, max deliver 2500psig, includes inlet/outlet gages, brass.</td>
<td>Linde</td>
<td>Matheson 3040</td>
<td>759.90</td>
<td>1</td>
<td>759.90</td>
</tr>
<tr>
<td>4</td>
<td>Tee</td>
<td>1/4&quot;NPT(F) x1/4&quot;NPT(F) branch x 1/4&quot;NPT(M)</td>
<td>Brass, Pressure 3600psig</td>
<td>Swagelok</td>
<td>B-4-ST</td>
<td>15.02</td>
<td>3</td>
<td>45.06</td>
</tr>
<tr>
<td>5</td>
<td>Pressure relief valve</td>
<td>1/4&quot;NPT(M)</td>
<td>Brass high-pressure ASME pop-safety valve, opens upon reaching set pressure.</td>
<td>McMaster</td>
<td>5825T21 &quot;3000psi&quot;</td>
<td>74.87</td>
<td>1</td>
<td>74.87</td>
</tr>
<tr>
<td>6</td>
<td>Purge valve</td>
<td>1/4&quot;NPT(M)</td>
<td>Brass with &quot;manual bleed/vent&quot;, quarter-turn from finger tight to create leak-free seal. Requires wrench.</td>
<td>Swagelok</td>
<td>B-4P-4M</td>
<td>12.71</td>
<td>1</td>
<td>12.71</td>
</tr>
<tr>
<td>7</td>
<td>Hose</td>
<td>1/4&quot;NPT(F) x1/4&quot;NPT(F)</td>
<td>smooth bore nitrogen gas hose, PTFE with SS overbraid. rated to 3600psig, 4 feet length, bend radius 3.5&quot;</td>
<td>McMaster</td>
<td>5665K14</td>
<td>84.52</td>
<td>1</td>
<td>84.52</td>
</tr>
<tr>
<td>8</td>
<td>Pressure gauge</td>
<td>1/4&quot;NPT(M)</td>
<td>Liquid fillable utility gauge. 2.5&quot; dial. 0-3000psi range. Lower mount. 2.5% full scale accuracy. phosphor bronze internals.</td>
<td>Omega</td>
<td>PGUF-2SL-3000PSI/210BAR</td>
<td>28.00</td>
<td>1</td>
<td>28.00</td>
</tr>
<tr>
<td>9</td>
<td>Quick-disconnect stem</td>
<td>1/4&quot; NPT(M)</td>
<td>Full flow type. NO shut-off valve: system must be purged before disconnect to prevent hose wip. stainless, rated up to 6000psig.</td>
<td>Swagelok</td>
<td>SS-QF4-S-4PM</td>
<td>14.49</td>
<td>1</td>
<td>14.49</td>
</tr>
<tr>
<td>10</td>
<td>Quick-disconnect body</td>
<td>1/4&quot;NPT(M)</td>
<td>Full flow type: pour in suspension using funnel. NO shut-off valve: system must be purged before disconnect to prevent hose wip. Stainless, rated up to 6000psig.</td>
<td>Swagelok</td>
<td>SS-QF4-B-4PM</td>
<td>36.12</td>
<td>1</td>
<td>36.12</td>
</tr>
<tr>
<td>11</td>
<td>Sample cylinder</td>
<td>1/4&quot;NPT(F)x1/4&quot;NPT (F)</td>
<td>Double-ended DOT compliant sample cylinder, 500mL, rated to 5000psig. 23.5&quot; long, overall diam is 1.90&quot;, wall thickness 0.240&quot;.</td>
<td>Swagelok</td>
<td>316L-50DF4-500</td>
<td>393.33</td>
<td>1</td>
<td>393.33</td>
</tr>
<tr>
<td>12</td>
<td>Outage tube with adaptor</td>
<td>1/4&quot;NPT(M)x1/4&quot;NPT (T)</td>
<td>Stainless steel. for sampling from turbulent cloud. 1.12&quot; length can be cut down later. Price not firm.</td>
<td>Swagelok</td>
<td>SS-DMT4-F4-011</td>
<td>41.37</td>
<td>1</td>
<td>41.37</td>
</tr>
<tr>
<td>13</td>
<td>Nipple</td>
<td>1/4&quot;NPT(M)x1/4&quot;NPT (T)</td>
<td>Brass fitting with hex for easy installation. Require 9/16&quot; wrench. Overall length 1.40&quot;, 400psi</td>
<td>Swagelok</td>
<td>B-4-HN</td>
<td>4.41</td>
<td>1</td>
<td>4.41</td>
</tr>
<tr>
<td>14</td>
<td>Pipe cap</td>
<td>1/4&quot;NPT(F)</td>
<td>304 SS, round. drill through 0.19&quot; wall thickness. 1&quot; overall length. 3000psi</td>
<td>McMaster</td>
<td>45525K582</td>
<td>4.60</td>
<td>3</td>
<td>13.79</td>
</tr>
<tr>
<td>15</td>
<td>Gas line tape</td>
<td>-</td>
<td>Yellow teflon tape for gas lines, to be used on all NPT threads</td>
<td>any</td>
<td>-</td>
<td>5.00</td>
<td>1</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Total: $1,556.48
## PARTS BILL 200 - STRUCTURE

<table>
<thead>
<tr>
<th>Line</th>
<th>Part name</th>
<th>Description</th>
<th>Buy from</th>
<th>Price per unit ($ CDN)</th>
<th>Quantity</th>
<th>Cost x QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>baseplate</td>
<td>Al 6061-T6 Flat bar. 0.5x6.0x36.0 long.</td>
<td>Metalsupermarkets</td>
<td>54.26</td>
<td>1</td>
<td>54.26</td>
</tr>
<tr>
<td>2</td>
<td>stage angle guide rails</td>
<td>Al 6061-T6 flat bar. 0.25x1.5x4.00 long</td>
<td>Metalsupermarkets</td>
<td>4.71</td>
<td>2</td>
<td>9.42</td>
</tr>
<tr>
<td>3</td>
<td>side plate - stationary support</td>
<td>Al 6061-T6 flat bar. 1x2.5x6.00 long</td>
<td>Metalsupermarkets</td>
<td>11.93</td>
<td>2</td>
<td>23.86</td>
</tr>
<tr>
<td>4</td>
<td>top plate - stationary support</td>
<td>Al 6061-T6 square 0.5x6x6</td>
<td>Metalsupermarkets</td>
<td>7.54</td>
<td>1</td>
<td>7.54</td>
</tr>
<tr>
<td>5</td>
<td>I-beam under high-pressure fixation</td>
<td>Al 6061-T6 I-beam. 3 high x 2.5 wide x 0.188 x 20.0 long</td>
<td>Metalsupermarkets</td>
<td>27.67</td>
<td>1</td>
<td>27.67</td>
</tr>
<tr>
<td>6</td>
<td>angles for high-pressure fixation</td>
<td>Al 6061-T6 angle. 2x3x0.25x24 long</td>
<td>Metalsupermarkets</td>
<td>17.19</td>
<td>2</td>
<td>34.38</td>
</tr>
<tr>
<td>7</td>
<td>bar for governing angle</td>
<td>Al 6061-T6 flat bar. 0.5x2.5x16.0long</td>
<td>Metalsupermarkets</td>
<td>18.08</td>
<td>1</td>
<td>18.08</td>
</tr>
<tr>
<td>8</td>
<td>angle-bar guide rails</td>
<td>Al 6061-T6 flat bar. 0.25x2x16.0long</td>
<td>Metalsupermarkets</td>
<td>9.12</td>
<td>2</td>
<td>18.24</td>
</tr>
<tr>
<td>9</td>
<td>angle for angle-governing bolt</td>
<td>Al 6061-T6 angle. 0.75x0.75x0.125x6.00 long</td>
<td>Metalsupermarkets</td>
<td>4.02</td>
<td>1</td>
<td>4.02</td>
</tr>
<tr>
<td>10</td>
<td>silicone adhesive</td>
<td>General Electric Silicone II.</td>
<td>Home Depot</td>
<td>4.50</td>
<td>1</td>
<td>4.50</td>
</tr>
<tr>
<td>11</td>
<td>angle bracket</td>
<td>galvanized steel. 0.75&quot; leg length, 0.50&quot; width. Cat#046-1966-8</td>
<td>Canadian Tire</td>
<td>0.63</td>
<td>12</td>
<td>7.50</td>
</tr>
<tr>
<td>12</td>
<td>main hinge</td>
<td>stainless steel strap hinge # 1796A23</td>
<td>McMaster-Carr</td>
<td>44.24</td>
<td>1</td>
<td>44.24</td>
</tr>
<tr>
<td>13</td>
<td>angle governing hinge</td>
<td>stainless steel strap hinge # 1364A12</td>
<td>McMaster-Carr</td>
<td>16.00</td>
<td>1</td>
<td>16.00</td>
</tr>
<tr>
<td>14</td>
<td>padding</td>
<td>polyurethane foam sheet. 24&quot;x12&quot;x0.125&quot;, black non-adhesive, durometer 30A. Cat#8781K522</td>
<td>McMaster-Carr</td>
<td>67.96</td>
<td>1</td>
<td>67.96</td>
</tr>
<tr>
<td></td>
<td><strong>Total:</strong></td>
<td></td>
<td></td>
<td><strong>$337.67</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## PARTS BILL 300 - STAGE ASSEMBLY

<table>
<thead>
<tr>
<th>Line</th>
<th>Part name</th>
<th>Connections</th>
<th>Description</th>
<th>Buy from</th>
<th>Price per unit (SCDN)</th>
<th>Quantity</th>
<th>Cost x QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>linear stage Kit</td>
<td>AC/DC Transformer and date cables included, mount stage using QTY4 M3x6mm long socket head screws into baseplate (supplied by Zaber), mount splash shield and sample mounting plate with QTY4 M3 x 12mm long flat head capscrews into stage itself.</td>
<td>100mm travel, manual override, download software from Zaber. Cat # KT-LSM100A includes accessories.</td>
<td>Zaber</td>
<td>1,941.00</td>
<td>1</td>
<td>1,941.00</td>
</tr>
<tr>
<td>2</td>
<td>splash shield</td>
<td>clamped between sample mounting plate and stage by action of 4 M3 screws.</td>
<td>Polycarbonate, 16&quot;x12&quot;x0.093&quot;, Shear to required size.</td>
<td>Home Depot</td>
<td>16.50</td>
<td>1</td>
<td>16.50</td>
</tr>
<tr>
<td>3</td>
<td>sample mounting plate</td>
<td>Fastened to splash shield and stage by M3 screws, carries samples with any combination of eight of its protruding #8 screws using 2 metal clamps and wingnuts.</td>
<td>aluminum plate, 5&quot;x3&quot;x0.25&quot;</td>
<td>Metal Supermarkets</td>
<td>16.50</td>
<td>1</td>
<td>16.50</td>
</tr>
<tr>
<td>4</td>
<td>sampling mounting clamp</td>
<td>onto any two protruding #8 screws on sample mounting plate, fix with wingnuts</td>
<td>aluminum strip 2.6&quot;x0.5&quot;x0.125&quot;</td>
<td>any</td>
<td>3.00</td>
<td>2</td>
<td>6.00</td>
</tr>
<tr>
<td>5</td>
<td>plastic bag</td>
<td>to enclose entire splash shield, Zaber stage and stage baseplate and allow for full range of movement of stage. Punch holes for screws affixing stage angle via angle brackets and screws clamping together sample mounting plate, splash shield to stage.</td>
<td>transparent plastic bag, waterproof seams or seamless.</td>
<td>any</td>
<td>1.00</td>
<td>1</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>plate for 45 deg angles</td>
<td>fasten to stage angle guide rails and fasten to brackets/stage baseplate</td>
<td>Al 6061-T6 plate 0.5x4x4</td>
<td>Metalsupermarkets</td>
<td>13.94</td>
<td>2</td>
<td>27.88</td>
</tr>
<tr>
<td>7</td>
<td>plate for 15 deg angles</td>
<td>fasten to stage angle guide rails and fasten to brackets/stage baseplate</td>
<td>Al 6061-T6 plate, 0.5x 6x4</td>
<td>Metalsupermarkets</td>
<td>17.43</td>
<td>2</td>
<td>34.86</td>
</tr>
<tr>
<td>8</td>
<td>plate underneath stage</td>
<td>fasten to stage and fasten to brackets/stage angles</td>
<td>Al 6061-T6 plate, 0.5x3.5x12.0 long</td>
<td>Metalsupermarkets</td>
<td>30.14</td>
<td>1</td>
<td>30.14</td>
</tr>
</tbody>
</table>

**Total:** $2,073.88
## PARTS BILL 400 - MAGNETIC MIXER ASSEMBLY

<table>
<thead>
<tr>
<th>Line</th>
<th>Part name</th>
<th>Connections</th>
<th>Description</th>
<th>Buy from</th>
<th>Price per unit ($CDN)</th>
<th>Quantity</th>
<th>Cost x QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>permanent bar magnet, rectangular, plastic-sheathed</td>
<td>glue-gunned to rotor of computer fan</td>
<td>5cm x 3cm x 2cm, iron</td>
<td>Active Surplus</td>
<td>2.50</td>
<td>1</td>
<td>2.50</td>
</tr>
<tr>
<td>2</td>
<td>computer fan</td>
<td>magnet glued on top, anti-vibration screws in screw ports</td>
<td>Overall approx. 2.5&quot;x2.5&quot;x1.0&quot;, High current rating 0.45A</td>
<td>A-1 Electronics</td>
<td>4.00</td>
<td>1</td>
<td>4.00</td>
</tr>
<tr>
<td>3</td>
<td>mixer box</td>
<td>glued with silicone adhesive to cradle (L-angle) of magnetic mixer assembly</td>
<td>Box was labeled for 3.5&quot; floppy disks. Transparent paper inside to remain dry after immersion test.</td>
<td>Active Surplus</td>
<td>0.75</td>
<td>1</td>
<td>0.75</td>
</tr>
<tr>
<td>4</td>
<td>spacer for dampening in mixer box</td>
<td>glue 2 identical spacers, with silicone adhesive, to each other, the anti-vibration screws of the computer fan, and also to the base of the mixer box</td>
<td>Polyurethane foam sheet. Shore hardness 30A, thickness 0.125&quot;. Cut two 2.81&quot;x2.81&quot; squares. Available in bulk #8781K522</td>
<td>McMaster-Carr</td>
<td>5.00</td>
<td>2</td>
<td>10.00</td>
</tr>
<tr>
<td>5</td>
<td>resistor for line to magnetic mixer</td>
<td>20 Ohm</td>
<td></td>
<td>Creatron</td>
<td>0.10</td>
<td>4</td>
<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>resistor for line to magnetic mixer</td>
<td>100 Ohm</td>
<td></td>
<td>Creatron</td>
<td>0.10</td>
<td>2</td>
<td>0.20</td>
</tr>
<tr>
<td>7</td>
<td>rotary switch</td>
<td>mount through hole in scrap angle. Switches between no power to mixer / line through 800Ohm for startup / 200OHM steady state mixing</td>
<td>4 position</td>
<td>Creatron</td>
<td>3.50</td>
<td>1</td>
<td>3.50</td>
</tr>
<tr>
<td>8</td>
<td>anti-vibration screws</td>
<td>inserted into screw holes in fan, faces glue-gunned to rubber spacers inside magnetic mixer enclosure</td>
<td>4 screws in pack</td>
<td>NTC Nanotek Computers</td>
<td>4.50</td>
<td>1</td>
<td>4.50</td>
</tr>
<tr>
<td>9</td>
<td>Wire spool</td>
<td>supply power from control circuit to magnetic mixer</td>
<td>Solid, 22 AWG, brown</td>
<td>Creatron</td>
<td>4.25</td>
<td>1</td>
<td>4.25</td>
</tr>
<tr>
<td>10</td>
<td>AC/DC transformer</td>
<td>supply power to control circuit</td>
<td>110/220VAC to 12VDC</td>
<td>A-1 Electronics</td>
<td>4.50</td>
<td>1</td>
<td>4.50</td>
</tr>
<tr>
<td>11</td>
<td>cradle</td>
<td>glue to box for mixer, fasten to neck</td>
<td>L-angle 3&quot;x3&quot;x0.125&quot;x3.5&quot; long</td>
<td>Metal Supermarkets</td>
<td>14.5</td>
<td>1</td>
<td>14.50</td>
</tr>
<tr>
<td>12</td>
<td>neck</td>
<td>fastened to cradle with one screw, fastened to sliding arm with four screws.</td>
<td>Al 6061-T6 angle. 3.0&quot; one leg x 0.25&quot; thick x 8&quot; long. Price shown is for equivalent bar.</td>
<td>Metal Supermarkets</td>
<td>16.5</td>
<td>1</td>
<td>16.50</td>
</tr>
<tr>
<td>13</td>
<td>sliding arm</td>
<td>clamps onto stalk and fastens to neck</td>
<td>Uses knob to tighten and clamp itself to stalk</td>
<td>Existing laboratory equipment</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>14</td>
<td>stalk</td>
<td>fastened to baseplate for magnetic mixer assembly with threaded rod</td>
<td>Smooth stainless rod to mate with clamp of sliding arm</td>
<td>Existing laboratory equipment</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>15</td>
<td>baseplate for magnetic mixer assembly</td>
<td>fasten to stalk with threaded rod</td>
<td>Al 6061-T6 plate 6&quot;x 3.0&quot; one leg x 0.25&quot; thick</td>
<td>Metal Supermarkets</td>
<td>20.71</td>
<td>1</td>
<td>20.71</td>
</tr>
<tr>
<td>16</td>
<td>stir bar</td>
<td>free-spinning inside sample cylinder</td>
<td>Ovoid, teflon coated, overall dimensions 6.31mm x 15.74mm Cat#14512122</td>
<td>Fisher Scientific</td>
<td>3.36</td>
<td>1</td>
<td>3.36</td>
</tr>
<tr>
<td>17</td>
<td>pad underneath base plate</td>
<td>none.</td>
<td>Cut 6&quot;x3&quot; from sheet supplied elsewhere per Cat#8781K522</td>
<td>McMaster-Carr</td>
<td>5.00</td>
<td>1</td>
<td>5.00</td>
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</tbody>
</table>

**Total: $94.67**
## PARTS BILL 500 - ENCLOSURE ASSEMBLY

<table>
<thead>
<tr>
<th>Line</th>
<th>Part name</th>
<th>Connections</th>
<th>Description</th>
<th>Buy from</th>
<th>Price per unit ($CAD)</th>
<th>Quantity</th>
<th>Price x QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>front shield</td>
<td>bolt to corner braces</td>
<td>polycarbonate sheet. No tint. Transparent. 40.0&quot;x26.0&quot;x0.25&quot;</td>
<td>Park Plastics</td>
<td>81.85</td>
<td>1</td>
<td>81.85</td>
</tr>
<tr>
<td>2</td>
<td>rear splash guard</td>
<td>bolt to corner braces</td>
<td>polyethylene sheet. White. Opaque. 26.0&quot;x40.0&quot;x0.25&quot;</td>
<td>Park Plastics</td>
<td>36.80</td>
<td>1</td>
<td>36.80</td>
</tr>
<tr>
<td>3</td>
<td>side splash guard</td>
<td>bolt to corner braces</td>
<td>polyethylene sheet. White. Opaque. 18.0&quot;x26.0&quot;x0.25&quot;</td>
<td>Park Plastics</td>
<td>25.35</td>
<td>2</td>
<td>50.70</td>
</tr>
<tr>
<td>4</td>
<td>face shield</td>
<td>Use QTY2 6&quot; mending plates to fasten to blast shield</td>
<td>polycarbonate sheet. No tint. transparent. 18&quot;x24&quot;x0.093</td>
<td>Home Depot</td>
<td>33.14</td>
<td>1</td>
<td>33.14</td>
</tr>
<tr>
<td>5</td>
<td>corner brace</td>
<td>attach walls at corners</td>
<td>zinc-plated steel. two holes per leg. Leg length is 3&quot;</td>
<td>Canadian Tire</td>
<td>1.13</td>
<td>12</td>
<td>13.50</td>
</tr>
<tr>
<td>6</td>
<td>mending plate</td>
<td>Used to attach face shield to blast shield with hex bolts.</td>
<td>zinc-plated steel. 4 holes total. 4&quot; total length. Holes must align with holes in blast shield described by drawing.</td>
<td>Canadian Tire</td>
<td>2.50</td>
<td>1</td>
<td>2.50</td>
</tr>
<tr>
<td>7</td>
<td>under-sheet</td>
<td>none.</td>
<td>Al 6061-T6 sheet. 48x20x0.05. bend up 1.0&quot; up all four edges to form tray. cut as required. punch hole for drainage.</td>
<td>Metalsupermarkets</td>
<td>41.34</td>
<td>1</td>
<td>41.34</td>
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</table>

**Total:** $259.83
<table>
<thead>
<tr>
<th>Line</th>
<th>Part name</th>
<th>Connections</th>
<th>Description</th>
<th>Buy from</th>
<th>Price per unit ($CDN)</th>
<th>Quantity</th>
<th>Cost x QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>screw</td>
<td>stage guide rails to base plate #8 x 0.5&quot; long flathead Phillips</td>
<td>Home Depot</td>
<td>0.50</td>
<td>4</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>screw</td>
<td>vertical supports to baseplate via angle bracket #8 x 0.5&quot; long flathead Phillips</td>
<td>Home Depot</td>
<td>0.50</td>
<td>8</td>
<td>3.98</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>screw</td>
<td>rails for angle governing to baseplate via angle bracket #8 x 0.5&quot; long flathead Phillips</td>
<td>Home Depot</td>
<td>0.50</td>
<td>8</td>
<td>3.98</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>screw</td>
<td>horizontal plate in stationary support to vertcals of stationary support #8 x 0.5&quot; long flathead Phillips</td>
<td>Home Depot</td>
<td>0.50</td>
<td>8</td>
<td>3.98</td>
<td></td>
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<tr>
<td>5</td>
<td>bolt</td>
<td>short leaf of main hinge to horizontal plate of stationary support 5/16-18 x 0.75&quot; long hex head stainless</td>
<td>Home Depot</td>
<td>0.79</td>
<td>3</td>
<td>2.37</td>
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<tr>
<td>6</td>
<td>bolt</td>
<td>long leaf of main hinge to to l-beam 5/16-18 x 0.75&quot; long hex head stainless</td>
<td>Home Depot</td>
<td>0.79</td>
<td>4</td>
<td>3.16</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>nut</td>
<td>long leaf of main hinge to to l-beam 5/16-18 hex nut stainless</td>
<td>Home Depot</td>
<td>0.59</td>
<td>4</td>
<td>2.36</td>
<td></td>
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<tr>
<td>8</td>
<td>bolt</td>
<td>l-beam to L-angles clamping sample cylinder 1/4-20x0.50 long hex head stainless</td>
<td>Home Depot</td>
<td>0.39</td>
<td>4</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>bolt</td>
<td>L-angles clamping sample cylinder to each other 5/16-18x3.0longx1.0&quot;thread hex head stainless</td>
<td>Home Depot</td>
<td>2.09</td>
<td>6</td>
<td>12.54</td>
<td></td>
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<tr>
<td>10</td>
<td>nut</td>
<td>L-angles clamping sample cylinder to each other 5/16-18 hex stainless</td>
<td>Home Depot</td>
<td>0.59</td>
<td>6</td>
<td>3.54</td>
<td></td>
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<tr>
<td>11</td>
<td>bolt</td>
<td>l-beam to small hinge for angle governance 1/4-20 x 0.75&quot; long hex head stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>2</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>nut</td>
<td>l-beam to small hinge for angle governance 1/4-20 hex stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>2</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>bolt</td>
<td>small hinge for angle governance to angle-governing bar 1/4-20 hex head x 1.0&quot; long stainless</td>
<td>Home Depot</td>
<td>0.59</td>
<td>2</td>
<td>1.18</td>
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<tr>
<td>14</td>
<td>nut</td>
<td>small hinge for angle governance to angle-governing bar 1/4-20 hex stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>2</td>
<td>0.98</td>
<td></td>
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<tr>
<td>15</td>
<td>bolt</td>
<td>angle governing bar to rails for angle governance 3/8-16 x 4.0&quot; long x 1.0&quot; thread hex head stainless</td>
<td>Home Depot</td>
<td>3.59</td>
<td>1</td>
<td>3.59</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>nut</td>
<td>angle governing bar to rails for angle governance 3/8-16 hex stainless</td>
<td>Home Depot</td>
<td>0.69</td>
<td>1</td>
<td>0.69</td>
<td></td>
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<tr>
<td>17</td>
<td>screw</td>
<td>Zaber linear stage to stage baseplate M3 x 5mm long socket head stainless</td>
<td>provided by manufacturer</td>
<td>0.00</td>
<td>4</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>screw</td>
<td>clamping sample mounting plate, stage splash shield to linear stage M3 x 10mm long cap screw flathead, only available in large quantities, stainless</td>
<td>McMaster-Carr</td>
<td>0.04</td>
<td>4</td>
<td>0.18</td>
<td></td>
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<tr>
<td>19</td>
<td>screw</td>
<td>clamping sample to sample mounting plate #8 x 1.0&quot; long flathead Phillips stainless</td>
<td>Home Depot</td>
<td>0.50</td>
<td>8</td>
<td>3.98</td>
<td></td>
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<tr>
<td>20</td>
<td>wingnuts</td>
<td>clamping sample to sample mounting plate #8 stainless</td>
<td>Home Depot</td>
<td>0.59</td>
<td>4</td>
<td>2.36</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>bolt</td>
<td>fixation of stage assembly to stage rails on baseplate 1/4-20 x 1.5&quot; long x 0.75&quot; thread hex head stainless</td>
<td>Home Depot</td>
<td>0.69</td>
<td>4</td>
<td>2.76</td>
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<tr>
<td>22</td>
<td>washer</td>
<td>fixation of stage assembly to stage rails on baseplate round, thin for 1/4-20 bolt stainless</td>
<td>Home Depot</td>
<td>0.39</td>
<td>4</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>nut</td>
<td>fixation of stage assembly to stage rails on baseplate 1/4-20 hex stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>4</td>
<td>1.96</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>threaded</td>
<td>rod fixation of stage assembly to stage baseplate of magnetic mixer assembly 1/4-20 rod 5/8&quot; long, cut from bolt if required, stainless</td>
<td>Home Depot</td>
<td>0.69</td>
<td>1</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>screw</td>
<td>sliding arm of magnetic mixer assembly to neck of magnetic mixer #8 x 0.75&quot; long flathead Phillips stainless</td>
<td>Home Depot</td>
<td>0.50</td>
<td>4</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>locknut</td>
<td>sliding arm of magnetic mixer assembly to neck of magnetic mixer #8 stainless nylon insert</td>
<td>Home Depot</td>
<td>0.42</td>
<td>4</td>
<td>1.66</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>bolt</td>
<td>neck of magnetic mixer support to cradle (L-angle) holding magnetic mixer box - rotational axis 1/4-20 x 0.75&quot; long hex head stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>1</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>nut</td>
<td>neck of magnetic mixer support to cradle (L-angle) holding magnetic mixer box - rotational axis 1/4-20 stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>1</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>bolt</td>
<td>neck of magnetic mixer support to cradle (L-angle) holding magnetic mixer box - fixation by tightening against cradle 1/4-20 x 0.75&quot; long hex head stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>2</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>bolt</td>
<td>neck of magnetic mixer support to cradle (L-angle) holding magnetic mixer box - fixation by tightening against cradle 1/4-20 x 0.75&quot; long hex head stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>2</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>washer</td>
<td>4 walls of enclosure and angle brackets round, thin for 1/4-20 bolt</td>
<td>Home Depot</td>
<td>0.39</td>
<td>42</td>
<td>16.38</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>nut</td>
<td>4 walls of enclosure and angle brackets 1/4-20 hex stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>42</td>
<td>20.58</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>bolt</td>
<td>blast shield of enclosure to mending plate 1/4-20 x 0.75&quot; long hex head stainless</td>
<td>Home Depot</td>
<td>0.49</td>
<td>4</td>
<td>1.96</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>nut</td>
<td>blast shield of enclosure to mending plate 1/4-20 stainless</td>
<td>Home Depot</td>
<td>0.39</td>
<td>4</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>washer</td>
<td>blast shield of enclosure to mending plate round, thin for 1/4-20 bolt</td>
<td>Home Depot</td>
<td>0.49</td>
<td>4</td>
<td>1.96</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>bolt</td>
<td>face shield of enclosure to mending plate 1/4-20 x 0.50&quot; long hex head stainless</td>
<td>Home Depot</td>
<td>0.39</td>
<td>4</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>nut</td>
<td>face shield of enclosure to mending plate 1/4-20 stainless</td>
<td>Home Depot</td>
<td>0.39</td>
<td>4</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>washer</td>
<td>face shield of enclosure to mending plate round, thin for 1/4-20 bolt</td>
<td>Home Depot</td>
<td>0.49</td>
<td>4</td>
<td>1.96</td>
<td></td>
</tr>
</tbody>
</table>

Total: $135.08
NOTE:
1. MAGNETIC MIXER (SEE DRAWING) PLACED TO MAGNET AS CLOSE AS POSSIBLE TO SAMPLE CYLINDER.

STAND FOR MAGNETIC MIXER

HIGH PRESSURE FIXATION

QUICK-DISCONNET FOR CONNECTION TO AIR.

STAGE ASSEMBLY

ENCLOSED JET

FRONT SHIELD REMOVED

BAR FOR FIXING ANGLE

RAILS FOR FIXING ANGLE WITH THRU-BOLT
DETAIL A
SCALE 2 : 5

SEE DRAWING FOR
CUT PADDING FOR
SAMPLE CYLINDER:
SIDE AND
UNDERNEATH.

NOTES:
1. ASSEMBLY PER INSTRUCTION IN PB 200, 600
2. PADS MAY BE GLUED TO ANGLES WITH PB200 LINE 10.
3. PIPING CONNECTIONS MUST BE SEALED WITH PB100 LINE 15.
Cradle can be angle with respect to neck by turning around thru-bolt and tightening with blind bolts.

Glue box to angle with PB200 line 10.

Note: Fasten per instruction in PB400, PB600.
NOTES:
1. ASSEMBLY PER INSTRUCTION IN PB 300, 600.
2. 45 DEG AND 15 DEG ANGLES ARE INTERCHANGEABLE.
3. ASSEMBLY AROUND STAGE MUST BE WATER TIGHT.
NOTES:
1. ASSEMBLY PER INSTRUCTION IN PB 200, 600.
2. PB500 L7 TO BE USED UNDERNEATH.

DETAIL A
TYPICAL CONNECTION USING PB500 L5.

SIDE GUARDS COVER ENDS OF FRONT AND REAR PANELS.
DRILL THRU HOLE DIAM 0.006" WITH EDM

SECTION B-B

FACE DOWN PIPE CAP TO SHOWN CAPELLARY LENGTH

PB100 L14

NOZZLE
NOTES:
1. ALL CONNECTIONS ARE ¼"NPT UNLESS OTHERWISE STATED.
2. SEAL ALL NPT CONNECTIONS WITH WHITE TEFLO TAPE.
3. SYSTEM MUST BE PURGED VIA MANUAL PURGE VALVE BEFORE DISASSEMBLY OF QUICK-DISCONNECT.
4. ALL COMPONENTS RATED TO 3000PSI OR HIGHER.
1/4" NPT MALE

SEE PARTS BILL FOR QUICK DISCONNECT TYPE

REF 1.57

REF .87

REF .69

PB 100 L10

QUICK DISCONNECT BODY

STANDARD PART
4X \( \varnothing .14 \)
\( \varnothing .19 \times 90^\circ \), NEAR SIDE

2X \( \varnothing .25 \)

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL \( \pm \frac{1}{32}^\circ \)
TWO PLACE DECIMAL \( \pm 0.005 \)
THREE PLACE DECIMAL \( \pm 0.0005 \)

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GOVERNING BAR AND BOLT BRACKET - ANGLE PB200 L9

1.00
0.50
0.75
0.440
0.125

0.75
0.50
0.25
0.425

DIMENSIONS ARE IN INCHES TO LAYERS 1/32" TOLERANCES:

- FRACTIONAL: ± 1/32"
- TWO PLACE DECIMAL: ± 0.005
- THREE PLACE DECIMAL: ± 0.0005

TOLERANCES:

- FRACTIONAL: ± 1/32"
- TWO PLACE DECIMAL: ± 0.005
- THREE PLACE DECIMAL: ± 0.0005

UNLESS OTHERWISE SPECIFIED:

- MATERIAL: PB200 L9
- FINISH: -
- APPLICATION: DO NOT SCALE DRAWING

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3 x \( \phi .2010 \)

Drill & Tap 1/4-20 from opposite side

\( \phi .3125 \) clearance holes for 5/16" bolts

Dimensions are in inches. Tolerances:
- Fractional: \( \pm 1/32" \)
- Two place decimal: \( \pm 0.005 \)
- Three place decimal: \( \pm 0.0005 \)

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2X \( \Phi .38 \) THRU

2X \( \Phi .14 \) THRU

\( \Phi .19 \times 90^\circ \) NEAR SIDE

THIRD ANGLE PROJECTION

ANGLE GOVERNING

PB200 L8

DIMENSIONS ARE IN INCHES

TOLERANCES:
FRACTIONAL \( \pm \frac{1}{32}'' \)
TWO PLACE DECIMAL \( \pm 0.005 \)
THREE PLACE DECIMAL \( \pm 0.0005 \)

THREE PLACE DECIMAL
TOLERANCES: 0.005

TWO PLACE DECIMAL
TOLERANCES: 0.005

DIMENSIONS ARE IN INCHES

TOLERANCES:
FRACTIONAL \( \pm \frac{1}{32}'' \)
TWO PLACE DECIMAL \( \pm 0.005 \)
THREE PLACE DECIMAL \( \pm 0.0005 \)

DIMENSIONS ARE IN INCHES

TOLERANCES:
FRACTIONAL \( \pm \frac{1}{32}'' \)
TWO PLACE DECIMAL \( \pm 0.005 \)
THREE PLACE DECIMAL \( \pm 0.0005 \)

DIMENSIONS ARE IN INCHES

TOLERANCES:
FRACTIONAL \( \pm \frac{1}{32}'' \)
TWO PLACE DECIMAL \( \pm 0.005 \)
THREE PLACE DECIMAL \( \pm 0.0005 \)

DIMENSIONS ARE IN INCHES

TOLERANCES:
FRACTIONAL \( \pm \frac{1}{32}'' \)
TWO PLACE DECIMAL \( \pm 0.005 \)
THREE PLACE DECIMAL \( \pm 0.0005 \)

DIMENSIONS ARE IN INCHES

TOLERANCES:
FRACTIONAL \( \pm \frac{1}{32}'' \)
TWO PLACE DECIMAL \( \pm 0.005 \)
THREE PLACE DECIMAL \( \pm 0.0005 \)
CLEARANCE HOLES FOR 5/16" BOLTS
6 X \( \phi .3125 \)

DIRECTIONS:
- DRILL & TAP 1/4-20 FROM THIS SIDE
- FINISH

DIMENSIONS ARE IN INCHES
TOLERANCES:
- FRACTIONAL \( \pm 1/32" \)
- TWO PLACE DECIMAL \( \pm 0.005 \)
- THREE PLACE DECIMAL \( \pm 0.0005 \)

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RIGHT HAND ANGLE

PB200 L6
NEXT ASSY: USED ON FINISH
APPLICATION: DO NOT SCALE DRAWING
SIDE WITH 6 IDEN. HOLES IS TOP.

2.121
.380

2 X φ .26 CLEAR FOR 1/4-20

2.00
.50

4X φ .257 THRU CLEAR FOR 1/4-20

19.09
9.81
1.00
NOTE: M3 TAPPED MOUNTING HOLES FOR STAGE SPACED PER SUPPLIER'S DRAWINGS.

Dimensions are in inches. Tolerances: Fractional ±1/32". Two place decimal ±0.005. Three place decimal ±0.0005.

Third Angle Projection

BASE PLATE - STAGE

PB300 L8
NOTE: MOUNT ONTO PROTRUDING #8 SC REWS WITH WING NUTS

2X Ø .16 THRU ALL

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/32"
TWO PLACE DECIMAL ± 0.005
THREE PLACE DECIMAL ± 0.0005

MATERIAL
PB300 L4

APPLICATION
- NEXT ASSY USED ON FINISH - APPROVED APPLICATION
- DO NOT SCALE DRAWING

THIRD ANGLE PROJECTION

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NOTE: 8X HOLES USED FOR LONG #8 FLATHEAD SCREWS THAT PROTRUDE AND ALLOW MOUNTING OF CLAMPS.

4X \( \phi .134 \) THRU ALL
\( \sqrt{\phi .25 \times 90^\circ} \)

8X \( \phi .18 \) THRU ALL
\( \sqrt{\phi .33 \times 100^\circ} \)
NOTES:
1. SOLDER ALL CONNECTIONS.
2. 200Ω LINE IS FOR STEADY STATE.
3. 80Ω IS FOR START-UP ONLY.
4. DANGER OF OVERHEATING IF USE 80Ω LINE IN CONTINUOUS OPERATION.
NOTE: STANDARD PART ALONG WITH PB400 LINE 12.

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SLIDING BRACKET - MAGNETIC MIXER ASSEMBLY

PB400 L13

DIMENSIONS ARE IN INCHES TO NEAREST 1/32"
TOLERANCES: THREE PLACE DECIMAL ± 0.005
TWO PLACE DECIMAL ± 0.005
FRACTIONAL ± 1/32"

UNLESS OTHERWISE SPECIFIED:

MATERIAL: PB400 L13

FINISH: -

APPLICATION: DO NOT SCALE DRAWING

NAME DATE
A.W. 11/21/2010

THIRD ANGLE PROJECTION

NAME
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES TO NEAREST 1/32"
TOLERANCES: THREE PLACE DECIMAL ± 0.005
TWO PLACE DECIMAL ± 0.005
FRACTIONAL ± 1/32"

UNLESS OTHERWISE SPECIFIED:

MATERIAL: PB400 L13

FINISH: -

APPLICATION: DO NOT SCALE DRAWING

NAME DATE
A.W. 11/21/2010

THIRD ANGLE PROJECTION

NAME

DIMENSIONS ARE IN INCHES TO NEAREST 1/32"
TOLERANCES: THREE PLACE DECIMAL ± 0.005
TWO PLACE DECIMAL ± 0.005
FRACTIONAL ± 1/32"

UNLESS OTHERWISE SPECIFIED:

MATERIAL: PB400 L13

FINISH: -

APPLICATION: DO NOT SCALE DRAWING

NAME DATE
A.W. 11/21/2010

THIRD ANGLE PROJECTION

NAME

DIMENSIONS ARE IN INCHES TO NEAREST 1/32"
TOLERANCES: THREE PLACE DECIMAL ± 0.005
TWO PLACE DECIMAL ± 0.005
FRACTIONAL ± 1/32"

UNLESS OTHERWISE SPECIFIED:

MATERIAL: PB400 L13

FINISH: -

APPLICATION: DO NOT SCALE DRAWING

NAME DATE
A.W. 11/21/2010

THIRD ANGLE PROJECTION

NAME

DIMENSIONS ARE IN INCHES TO NEAREST 1/32"
TOLERANCES: THREE PLACE DECIMAL ± 0.005
TWO PLACE DECIMAL ± 0.005
FRACTIONAL ± 1/32"

UNLESS OTHERWISE SPECIFIED:

MATERIAL: PB400 L13

FINISH: -

APPLICATION: DO NOT SCALE DRAWING

NAME DATE
A.W. 11/21/2010

THIRD ANGLE PROJECTION

NAME
**NOTE:** STANDARD PART BOUGHT ALONG WITH SLIDING ARM PB400 LINE13.

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**STALK - MAGNETIC MIXER ASSEMBLY**

**STANDARD PART**

<table>
<thead>
<tr>
<th>SIZE</th>
<th>DWG. NO.</th>
<th>REV</th>
<th>DESCRIPTION</th>
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<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>PB400 L14</td>
</tr>
</tbody>
</table>

**UNLESS OTHERWISE SPECIFIED:**

- DIMENSIONS ARE IN INCHES TO TOLERANCES:
  - FRACTIONAL ± 1/32" 
  - TWO PLACE DECIMAL ± 0.005
  - THREE PLACE DECIMAL ± 0.0005

**THIRD ANGLE PROJECTION**

**REF 14**

**REF Ø 1.5**

**DRILL AND TAP 1/4-20 X 0.5/16 DEEP FOR THREADED DO WEL.**

**NOTE:** STANDARD PART BOUGHT ALONG WITH SLIDING ARM PB400 LINE13.
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TITLE:
FRONT SHIELD - ENCLOSURE

SIZE: A
DWG. NO.: 0
REV.

PB500 L1

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/32"
TWO PLACE DECIMAL ± 0.005
THREE PLACE DECIMAL ± 0.0005

UNLESS OTHERWISE SPECIFIED:

MATERIAL
FRONT SHIELD - ENCLOSURE

THIRD ANGLE PROJECTION

APPLICATION

DO NOT SCALE DRAWING

2.00
14.50
9.00
3.50
18X Ø .25 THRU
.90
2.50
.25
.98
2.58
40.00
26.00
24.00
13.00